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A GENERIC STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY PROGRAM FOR THE ARMY

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MATERIEL DURABILITY BRANCH

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ABSTRACT

A Generic Structural Integrity Assurance Technology Program is presented which is applicable to all Army materiel systems. The technology program is organized and written in the format of a standard to demonstrate the potential for formalized program development. The relationship between such a program and possible Army and U.S. Army Materiel Command (AMC) regulations is indicated. The program covers all tasks over the life of the system, design information, analysis and material characterization, design development testing, qualification testing, and life management. The generic program requires the development of mission specific structural integrity programs for particular classes of materiel structures based on the generic program guidelines. The generic program incorporates a new generalized concept which defines structural integrity parameters for resistance to maximum loading and service life. These parameters must be evaluated on the basis of an integrated qualification testing and in-service program by acceptance criteria formally specified by the major subordinate command. A service life base line parameter is defined which characterizes the nominal behavior of a system. A service life design sufferance parameter is defined and illustrated which characterizes "other than nominal" conditions which are a major influence on safety. Design sufferance conditions are general and may involve damage tolerance or any other design conditions which may deviate from base line conditions. Limited duration service life unrepaired/repaired damage parameters are defined for those unique design conditions. The generalized approach requires that detailed structural quantities must be defined and supporting basis and rationale documented.

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INTRODUCTION

The U.S. Army fields many materiel systems in which structural integrity deficiencies can have serious consequences. Examples of such systems are helicopters, missile and armament systems, tanks and vehicles, and bridging and antenna structures. Structural integrity deficiencies can influence mission performance, safety, readiness, and costs. Historically, the Army has dealt with its structural integrity needs through a variety of approaches applied by each of the major subordinate commands (MSC's) to the materiel systems for which they are responsible. Most of these approaches have not been formalized through standards and specifications and the formalization that does exist is in need of modernization. Past approaches in the Army to structural integrity and the issues related to a formalized Army Generic Structural Integrity Assurance Technology Program are discussed more fully in References 1 and 2.

Structural integrity assurance (SIA) is defined in relation to this program as the assurance that critical load-carrying components do not fail in the service environment during a specified lifetime. The SIA program is a set of formal regulations, standards, and specifications. It is proposed in Reference 1 that the most useful approach to meet the overall SIA needs of the Army would be to develop a generic SIA standard. The generic SIA standard would establish a uniform Army approach in three broad areas. First, the organization and integration of SIA tasks for structural design, development, qualification, and life management; i.e., a "cradle to grave" program. Second, to establish requirements for SI parameters which must be evaluated to characterize the SI of a materiel system. Third, to establish guidelines for the quality of individual SI subtasks. A proposed hierarchy of formalization is shown in Figure 1. The Army regulation would establish policy for all major commands. A U.S. Army Material Command (AMC) regulation may be necessary to provide detailed policy for its major subordinate commands. As discussed in Reference 2, the close interrelationships between SI issues and mission performance, safety, readiness, and cost issues for which an MSC is responsible is such that decisions concerning methods and quantitative requirements adopted for a specific mission area must be the responsibility of the MSC. Therefore, a mission specific SIA standard would be required to be developed by the responsible Army organization within the framework and guidelines of the generic standard. The detailed Army generic technology SIA program is presented in the Supplement Section of this report.

SUMMARY OF GENERIC SIA TECHNOLOGY PROGRAM

Organizational Format

The program establishes five major tasks: design information, analysis and material characterization, design development testing, qualification testing and life management data, and life management.

Critical Components

The program requires that a critical structural component parts list be established for each materiel system covered by the program.

1. *Assuring Structural Integrity in Army Systems*. National Material Advisory Board, National Research Council Report, NMAB-117, February 28, 1985.
2. MATTHEWS, W. T. *Generalized Structural Integrity Assurance Technology: Application to Army Generic Structural Integrity Assurance Technology Program*. U.S. Army Materials Technology Laboratory, AMTL-TR 89-88, September 1989.

SI Requirements

The program establishes the following major parameters to be evaluated to characterize the structural integrity of the critical components of a materiel system.

Maximum Loading Resistance: Evaluation of strength, deformation, and buckling resistance of structure.

Service Life - Base Line Design: Evaluation of the service life or the time intervals for major inspections of the vast majority of the materiel systems in service. Life is evaluated for both fatigue dominated and static load degradation dominated service conditions. This parameter characterizes the nominal operational life of the materiel system.

Service Life - Design Sufferance: Evaluation of the tolerance of the structure to conditions that vary from the base line design which may be experienced by some of the materiel systems in service. Possible conditions to be evaluated are broad, including initial flaws, in-service damage, loss of conditions which inhibit fatigue damage initiation and growth, and environment degradation.

Limited Duration Service Life - Survivability Design: (a) Evaluation of the capability of a materiel system to complete one mission after extensive specified damage and (b) evaluation of the capability of the materiel system to complete a specified number of missions after field repair of damage.

Flexibility: The generic program permits flexibility in developing methods to evaluate the SI requirements. However, testing is required to validate modeling and analytical methods.

Advanced Materials: The generic program describes the "building block" approach of development design with advanced materials where the current state of technology is such that interrelated issues of complex loading and design configuration, material behavior, and environmental effects cannot, in general, be separated and evaluated. The building block approach involves the testing of coupons, elements, subcomponents, and components.

Documentation: The program requires that the basis and rationale for mission definition, analysis and testing methods, and qualification test criteria be documented in a form suitable for proper interpretation of interrelated tasks; e.g., qualification test evaluation, development of in-service programs, and implementation of life management programs including effects of mission changes and life extension.

Commentary

The detailed generic program described in the Supplement Section is aimed at fulfilling the objective of providing a formal disciplined framework with accompanying technical guidelines suitable for the development of mission specific SIA technology programs for all types of materiel systems. Particular issues are cited in this generic program to illustrate the features and concerns related to the SIA program. Other issues could be cited from the wide range of SIA related issues. It is recognized that the completely satisfactory, widely accepted, general technical methods are not currently available to characterize SIA in all materiel systems. Further, with continued opportunities for innovative designs using emerging materials, there may always be difficulties in the availability of completely satisfactory methods for application to SIA programs. However, a formalized SIA program can provide guidelines for

development of interim procedures and the program format may be useful in documenting the need for the development of improved technical methods for application to emerging materials.

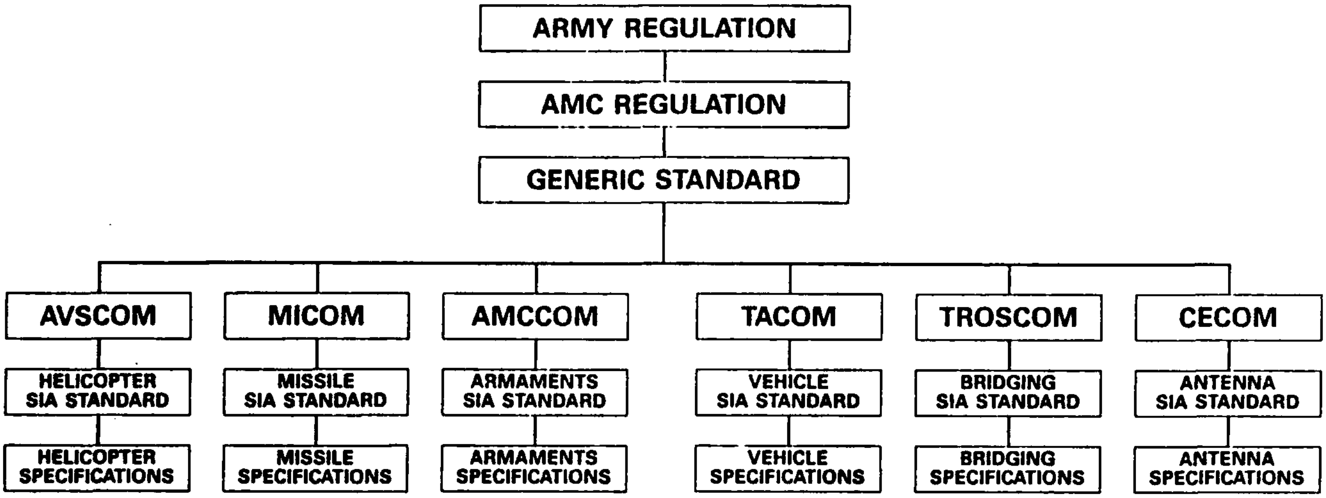

Figure 1. Army structural integrity assurance program.*

*Specific titles are intended only to illustrate possible application to materiel systems and relationships between formal documents.

SUPPLEMENT

ARMY GENERIC STRUCTURAL INTEGRITY

ASSURANCE TECHNOLOGY PROGRAM

SCOPE

Purpose

The purpose of this document is to describe a Generic Structural Integrity Assurance (SIA) Technology Program for the Army and to define tasks necessary to evaluate structural integrity of Army materiel systems. The program would be used by:

(a) An Army MSC in developing a mission specific SIA standard and supporting specifications.

(b) A materiel system developer in meeting the structural integrity needs of a particular materiel system development in the absence of a completed mission specific SIA standard.

(c) Army personnel in managing the design development, qualification, and operational support of a particular system in the absence of a completed mission specific SIA standard.

Applicability

Type of Structure

(a) The program is directly applicable to all Army materiel systems where structural failure would impact safety, readiness, cost, and maintenance. Such systems would include helicopters, VTOL aircraft, missiles, armaments, combat and support vehicles, and structures such as bridging and antennas.

(b) The program is applicable to structures within these identified materiel systems for which solid mechanics methods (stress, strain, deflection, buckling, yielding, fracture, and flaw propagation) are most appropriate and useful for characterizing structural integrity. Also included are subsystem structures which are not primarily designed from a structural integrity viewpoint, such as ballistic systems and helicopter crashworthy systems. The design of such systems may involve decisions concerning design details and material selection, and processing and inspection methods which may also influence structural integrity of the subsystem or total system. Mechanical system components such as bearings, gears, seals, pumps and valves, and avionic systems are not covered by this program since specific industry standards, based on extensive industry experience, are currently the most appropriate basis for establishing satisfactory performance.

Type of Materiel System

The SIA program applies to:

(a) Future Army materiel systems.

(b) Materiel systems modified or directed to new missions.

(c) Materiel systems procured by the Army but developed under auspices of another regulatory agency.

Type of Material

This program applies to all types of structural material; metallic and nonmetallic.

Materiel System Development

This program shall be applied to all phases of materiel system development: conceptual, demonstration/validation, full scale development, and production.

Modifications

The responsible Army organizations shall develop mission specific SIA standards and supporting specifications within the framework of this generic program. The generic program establishes major requirements and describes tasks and subtasks in general items to permit flexibility in addressing SI issues for particular materiel systems. If mission specific SIA standards contain features which are not within the framework of this generic standard, the rationale and supporting information should be presented in an addendum to the mission specific SIA standard.

REFERENCED DOCUMENTS

Standards

MIL-STD-1530A	Aircraft Structural Integrity Program, Airplane Requirements, 11 Dec 1975.
MIL-STD-2069	Requirements for Aircraft Non-Nuclear Survivability Program, 1981.

Handbooks

MIL-HDBK-5	Metallic Materials and Elements for Aerospace Structures
MIL-HDBK-17	Polymer Matrix Composites
MIL-HDBK-729	Corrosion and Corrosion Prevention of Metals
MIL-HDBK-735	Material Deterioration Prevention and Control
	Engineering Design Handbook

Other

AASHTO	Standard Specifications for Highway Bridges, 12th ed., The American Association of State Highway and Transportation Officials, Washington, DC, 1977.
AISC	Bridge Fatigue Design Guide, American Institute of Steel Construction, Chicago, 1977.
AISC	Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings, 1978.

Aluminum Association	Specifications for Aluminum Bridge and Other Highway Structures, 1976.
Aluminum Association	Specifications for Aluminum Structures, Third Edition, 1976.
ASME	ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers, 1986.

DEFINITIONS AND ACRONYMS

Definitions

A-Basis: At least 99 percent of the population of values is expected to equal or exceed the A-basis mechanical design material property with a confidence of 95 percent.

B-Basis: At least 90 percent of the population of values is expected to equal or exceed the B-basis mechanical design material property with a confidence of 95 percent.

Base Line Design: The nominal characterization of a design which pertains to the vast majority of the total number of each of the critical components.

Building Block Design Development Method: Testing approach to develop design characterization where general analytical methods for dealing with configuration complexities, environmental conditions, material characterization, and property variability of advanced materials is lacking. The process involves a series of tests of increasing geometric complexity (coupons, elements, subcomponents, and components).

Component: A major section of a materiel system structure.

Condition of Structure: The definition of the nature and extent of permissible damage in a qualification test.

Coupon: A small test specimen with simple geometry for evaluation of basic properties or phenomena.

Crack Arrest Structure: Structure with design features (configuration and/or material) which are capable of stopping unstable rapid fracture propagation within a continuous area of a structure.

Critical Part: A structure or portion of a structure whose failure could cause catastrophic failure of the materiel system either immediately or if the failure remained undetected.

Detail: A nongeneric structural element or portion of a structure.

Design Allowable: Material characterization for structural design derived from tests which involve specific geometric features and specific associated structural behavior.

Design Sufferance: The characterization of the structural design which pertains to a small minority of the total number of each critical component for which any of the conditions may deviate from the nominal design conditions.

Element: A generic structural element of a more complex structure.

Failure/Flaw Detection System: An in-situ system capable of detecting flaws or failures which can be monitored continuously or intermittently.

Initial Quality: A measure of the condition of a structure relative to flaws, defects, or other material features detrimental to SI inherently present in the material or introduced during manufacture and assembly of the structure.

Knockdown Factor: A factor which reduces the allowable level of a material property, such as strength, to account for environmental effects.

Lead Force: An identified group of in-service materiel systems that are subjected to the more severe service conditions of the defined mission spectra early in their service life.

Leak Before Break: Resistance to failure of a structure in the presence of cracks or flaws of such a size that leakage of gas or liquid through the wall of the structure could occur.

Load Enhancement: A load increment which is added to the nominal loading to account for factors such as load variability, dynamic loading effects, or environmental effects.

Material Allowable: Material characterization derived from simple test specimens on a statistical or empirical basis.

Maximum Loading: Loading conditions which cause the "worst case" relative to all pertinent failure criteria for a particular local region or global region of a part or component.

Multiple Load Path (Redundant) Structure: Structure providing two or more separate and distinct paths of structure that will carry a specified design load after complete failure of one of the paths.

Nominal Characterization: A characterization which is defined, adopted, or derived from a finite size data base.

Nominal Conditions: Refer to nominal characterization.

Nominal Loading: Refer to nominal characterization.

Safe Life: The criterion that an "as manufactured" structure, as shown by tests or analysis based on tests, does not develop measurable cracks during the service life of a materiel system or before a scheduled replacement time.

Safety Factor: A factor applied in the evaluation of the safeness of a structural member or assemblage of members which accounts for uncertainties in the evaluating process.

Service Life Factor: A multiplying factor applied in the evaluation of the service life of a structure which accounts for uncertainties in the evaluating process.

Slow Crack Growth Structure: A design concept in which flaws or defects are not allowed to reach critical size associated with unstable rapid crack propagation. Safety is

assured through slow-crack growth for specified periods accompanied by appropriate inspections. The strength of the structure with damage present shall not be degraded below a specified limit for a period of unrepaired service.

Structural Integrity Assurance: The assurance that critical load-carrying components do fail in the service environment during a specified lifetime.

Subcomponent: A major structure which provides complete representation of a portion of a full structure.

Acronyms

FOS: Factor of Safety

K_{Ic}: A toughness property of a material obtained on the basis of linear elastic fracture mechanics by the ASTM Test Method E 399.

K_{IEAC}: A toughness measure of a materiel in the presence of a corrosive environment based on linear elastic fracture mechanics.

J_{Ic}: An elastic-plastic toughness measure of a material obtained by the ASTM Test Method E 813.

LEFM: Linear elastic fracture mechanics.

TECHNOLOGY PROGRAM SUMMARY

General Features

The overall program goal is to maintain adequate SI of Army materiel systems throughout the life cycle of the system. A structural integrity assurance plan is established for each materiel system. The system SI is established, evaluated, and documented for the design. In-service usage data is obtained and evaluated to provide continual assessment and updated documentation relating to system SI. In order to achieve these goals, the SI program features the following.

- Critical structural parts are identified.
- Primary SI parameters are defined to characterize SI.
- Analytical mechanics-based modeling methods are identified which are quantitative, predictive, and consistent throughout subtask application; for example, flaw based (damage tolerant) or nonflaw based (safe life method).
- Testing methods are required to validate analytical models.
- In-service loading is monitored and, if feasible, mechanics parameters and damage are monitored in service.
- A procedure is established to feedback in-service data to be assessed relative to documented materiel system SIA analysis.

- Design with advanced materials utilizes the "building block" approach through testing of coupons, elements, subcomponents, and components.

In view of the diversity of Army mission areas and associated emphasis on SI and the ongoing technology development of structural integrity methods related to advanced materials, the generic program considers SI, at the subtask level from various viewpoints. Typically, the subtask discussions begin with consideration of traditional mechanics issues and fundamentals with emphasis on factors which are intended to account for uncertainties and proceeds to advanced materials issues.

Organizational Format

The program consists of five interrelated functional tasks as outlined in Table 1.

(a) Task I. Design Information: Development of those criteria which must be applied during the design so that specific requirements will be met.

(b) Task II. Design Analysis and Material Characterization: Development of analysis of candidate functional designs and characterization of candidate materials.

(c) Task III. Design Development Testing: Testing of elements and subcomponents to validate analysis and develop strength and service life data for complex configurations and interrelated loading history, material, structural, and environmental effects.

(d) Task IV. Qualification Tests and Life Management Data: Testing to assess structural adequacy of the design. Documentation of final analyses, manufacturing quality control summary, and life maintenance plan.

(e) Task V. Life Management: SI monitoring, maintenance, and in-service data bank/feedback functions to ensure SI throughout the service life of the system.

Mission Specific SIA Standards

Mission specific SIA standards are prepared with tasks and subtasks organized and identified as outlined in the Organizational Format Section. Each task and subtask is addressed and appropriate details specified with rationale and basis documented consistent with the framework and guidelines of the Army Generic SIA Technology Program.

DETAILED TECHNOLOGY PROGRAM

Task I. Design Information

The design information task encompasses those efforts required to apply theoretical, experimental, applied research, and operational experience to the specific criteria for materials selection and structural design of materiel systems. The objective is to ensure that the appropriate criteria and planned usage are applied to a design so that specific operational requirements will be met. This task begins as early as possible in the conceptual phase of materiel system development.

Table 1. GENERALIZED STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY PROGRAM OUTLINE

TASK I Design Information	TASK II Design Analysis and Material Characterization	TASK III Design Development Testing	TASK IV Qualification Tests and Life Management Data	TASK V Life Management
A. SIA Plan 1. Operational Requirements 2. Mission Definition 3. Service Life & Environment Definition 4. Technical Approach Outline 5. Unique Technical Features 6. Scheduling	A. Max. Load Analyses	A. Service Load & Environmental	A. Max. Loading Resistance 1. *Structure* 2. Number of Tests 3. Loading & Environment 4. Instrumentation 5. Posttest Inspection 6. Test Evaluation	A. SIA Management
B. SIA Characterization 1. General 2. Max. Loading Resistance 3. Service Life - Base Line Design SI Parameter 4. Service Life - Design Sufferance SI Parameter 5. Limited Duration Service Life SI Parameter (Survivability) (a) Unrepaired Damage (b) *Repaired Damage* 6. Criteria for Measures of SI Parameters 7. Safety & Service Life Factors 8. Critical Parts List	B. Service Load Analyses	B. Joints - Mechanical Testing	B. Service Life - Base Line 1. Structure 2. Number of Tests 3. Loading & Environment 4. Test Duration 5. Residual Strength 6. Instrumentation & Posttest Inspection 7. Test Evaluation	B. Operational Limitation Program
C. Designing for SIA 1. Design - Max. Loading Resistance 2. Design - Service Life 3. Design - Limited Service Life 4. Structural Design Codes	C. Design Environment	C. Building Block: Advanced Material Testing	C. Service Life - Design Sufferance 1. Structure 2. Number of Tests 3. Loading & Environment 4. Test Duration 5. Residual Strength 6. Instrumentation & Posttest Inspection 7. Test Evaluation	C. Life SIA Maintenance Program
D. Service Life SIA Plan 1. Critical Parts List 2. Modeling Methods 3. Life Analysis Data Development 4. In-Service Damage Definition 5. Design Sufferance Issues 6. Building Block Issues 7. Quality Assurance Issues 8. Life Maintenance 9. Design Trade-Offs	D. Material Property Characterization 1. General 2. Material Allowables 3. Material Properties Summary	D. Max. Loading Resistance	D. Limited Duration Service Life 1. Unrepaired Damage 2. Repaired Damage	D. In-Service Usage Monitoring Program
E. Design Service Life & Usage	E. Mechanics Analyses	E. Service Life - Base Line Design	E. Qualification Test Summary & Corrective Actions	E. SIA Data Bank & Reporting Program
F. Materials, Processes & Joining Methods Selection	F. SI Analysis at Max. Loading	F. Service Life - Design Sufferance	F. Life Management Data Package 1. Manufacturing Q.A. Summary 2. Final SI Analysis Summary 3. Operational Limitation Plan 4. Life SIA Maintenance Plan 5. In-Service Usage Monitoring Plan 6. SIA Data Bank & Reporting Plan	
	G. Service Life Analysis 1. General (a) Service Life Factors (b) Residual Strength (c) Environment 2. Service Life - Base Line Design (a) Flaw Based Analysis (b) Nonflaw Based Analysis (c) Maximum Loading Resistance In-Service Degradation 3. Service Life Design Sufferance	G. Limited Duration Service Life 1. *Unrepaired Damage* 2. Repaired Damage	G. SIA Evaluation	
	H. Limited Duration Service Life Analysis (Survivability) 1. General 2. Unrepaired Damage - Analysis 3. Repaired Damage - Analysis	H. Manufacturing Q.A. Prequalification Summary		

Task I-A. Structural Integrity Assurance (SIA) Plan

An SIA plan shall be prepared for each materiel system development covered by a mission specific SIA program. The materiel system SIA plan shall include the following:

(1) System operational requirements.

(2) Mission definition.

(3) Service life duration and environment definition.

(4) SIA technical approach outline.

(5) Unique technical features and exceptions to Army SIA standards.

(6) Scheduling.

The SIA plan shall depict scheduling and integration of all required SIA tasks for design, development, qualification, and life management. The plan shall be updated and modified when required to reflect the status of the particular SIA materiel system program.

Task I-B. Structural Integrity Characterization

Task I-B1. General

The structural integrity of Army materiel systems must be characterized by suitable parameters which describe the SIA capability of the materiel system for all aspects of operation.

The Army Generic SIA Technology Program defines the required SI parameters as the following.

- Resistance to maximum loading
- Service life - base line design
- Service life - design sufferance
- Limited duration service life - unrepaired damage (survivability)
- Limited duration service life - repaired damage

The required SIA parameters shall be evaluated for all critical structural component parts. The Army Generic SIA Technology Program requires that a critical structural component parts list shall be established for each materiel system covered by the SIA program.

The SI parameters shall be evaluated for all loading and environmental conditions derived from the materiel system mission requirements as described in the SIA plan, Task I-A, and the design service life/usage, as described in Task I-D. The relationship between the loading conditions being considered and the associated mission requirements shall be clearly identified and documented throughout the SIA program. For example, the loading conditions may be average values or upper bound values associated with normal mission requirements. In addition, loading conditions may be average values or upper bound values associated with other-than-normal mission profiles. Other-than-normal mission profiles may arise from extreme or

emergency operations. The relationship between loading and mission profiles must be clearly identified and understood in order to make appropriate choices for factor of safety, service life factor, design sufferance conditions, and appropriate life management program described in Task IV-F. The mission specific SIA standard and specifications may specify loading/mission relationships, where appropriate.

The measures of these SI parameters and criteria for their allowable values is discussed in Task I-B6.

If data from design, development, qualification testing, and service experience is available to justify the omission of the evaluation of any one of the SI parameters for certain mission areas, materiel systems, or particular components of materiel systems, the rationale and supporting basis relating to the omission shall be documented at the appropriate level of SIA formalization. The documentation shall be part of the mission specific SIA standard, or supporting specifications, or as part of the materiel system SIA plan. The documentation shall cover all SI aspects of the design, development, qualification testing, or service usage and experience supporting the omission of the SI parameter in order to clearly indicate the criteria upon which the omission of the SI parameter is based.

Task I-B2. Resistance to Maximum Loading SI Parameter

The resistance of critical structural components to maximum loading conditions for the loadings described in Task I-A, and discussed in Task I-B1, shall be evaluated.

The SI parameter is expressed in terms of loading since for various structures and materials the maximum resistance to loading is governed by allowable strength, allowable strain limits, displacement, or buckling behavior. The evaluation is made with respect to initial design quality. Degradation in resistance to maximum loading is considered in the service life evaluations. The criteria for maximum allowable values of these measures of this SI parameter is discussed in Task I-B6. Methods for analysis and testing for this SI parameter are discussed in Task II-E, Task II-F, and Task III-D.

Task I-B3. Service Life - Base Line Design SI Parameter

The service life - base line design SI parameter shall be evaluated for all critical structural components for the loading described in Task I-B1. The service life - base line design SI parameter characterizes the service life pertaining to the vast majority of the total number of a critical component. If the characterization is in terms of life, then, typically, the design life is taken to be equal to the required system life multiplied by a service life factor. For critical parts where the design life is short, relative to the system life, so that it is necessary to replace these critical parts at scheduled intervals during service life, the design life would be equal to the scheduled interval life multiplied by an interval service life factor. The interval service life factor may be larger than the nominal service life factor related to full life since there is less time for averaging of variabilities to be effective.

The service life - base line model utilizes information derived from finite size data bases associated with the loading conditions, initial quality, fabrication processes (residual stresses), material properties, and in-service inspection quality. In some cases, the base line design quantities may be average values, and in other cases they may be limiting values such as statistically based A or B basis material properties or "top of scatter" quantities of spectrum

loading. By definition, the base line design SI parameter does not characterize the susceptibility of a materiel system to conditions which differ from the base line conditions.

Additional insight concerning the relationship between base line and design sufferance service life characterizations may be gained by reference to discussion in Task I-B4. An example of a design sufferance issue which is excluded from consideration in the base line design are large "rogue flaws" which have been shown to be present initially in some structures. The service life - base line design SI parameter characterizes the behavior of the structure in repeated load (fatigue) dominated service or in service dominated by material degradation under essentially static loads (e.g., in storage) or in service which includes both effects. Criteria for allowable values of measures of service life residual strength SI parameters are discussed in Task I-B6. Service life issues are discussed in Task I-D and Task II-G.

Task I-B4. Service Life - Design Sufferance SI Parameter

The service life - design sufferance SI parameter shall be evaluated for loadings described in Task I-B1. The service life - design sufferance evaluation characterizes the tolerance of the structure to conditions which deviate from the base line design which may be experienced by some materiel systems in service. The term "design sufferance" is used to indicate a broad range of possible deviations from the base line conditions. The conditions which are more severe than the base line conditions and may represent conditions which are most detrimental to the structural integrity are of interest. The design sufferance evaluation should consider the following.

- Explicit crack, flaw, damage model:
  When base line model is nonflaw based (safe life)
- Larger than nominal explicit initial:
  Cracks, flaws - metals, ceramics
  Damage - advanced materials
- Loss of near surface conditions which promote SI:
  Favorable residual stresses
  Environmental protection (corrosion, moisture)
- Unintended out of plane loading:
  Engineered/tailored materials
- Larger than nominal undetected impact damage
- Multiple site/wide scale damage and degradation

Design sufferance conditions may involve nonvisible, noninspectable conditions. The design, analysis, qualification, and life maintenance approach must provide a viable structural integrity assurance for such conditions.

In contrast to the broad range of design sufferance issues cited, the Air Force SI program, MIL-STD-1530A, considers only what is defined as damage tolerance. The Air Force damage tolerance approach considers the largest initial flaw which may escape detection by nondestructive testing and its subsequent growth. The Air Force approach was developed as the most appropriate approach for stiffened metallic shell airframe structures which contain thousands of rivet holes. The growth of flaws from rivet holes is a major concern in the Air Force SI program. If an Army structure were similar in design details, material, fabrication,

service usage inspection, and maintenance to the stiffened metallic airframe structure, then the Air Force damage tolerance approach and its associated quantitative flaw sizes could be chosen as the most appropriate approach to evaluate the service life - design sufferance parameter for the Army generic SI program.

In generic Army materiel system development, the nature of the evaluation depends upon the design situation. The evaluation could be in terms of reduced service life relative to the base line design for a specified mission spectrum. The evaluation could also be in terms of reduced strength (e.g., fatigue strength) for a specified service life period. In addition, the evaluation could be utilized to establish inspection intervals, sufficiently long to be practical, to avoid failure related to statistically infrequent design sufferance events.

The Army generic SIA program requires that the mission specific SIA standard and specifications shall, where feasible, identify service life - design sufferance issues to be addressed in materiel system development. This identification should be with regard to particular classes of critical structures. When such identification is not feasible in the mission specific SIA standard and its specifications, the standard shall require design sufferance issues to be studied, identified, and evaluated as part of the materiel system development. The rationale for selection of the design sufferance issues shall be documented in the Materiel System SI Analysis Summary, described in Task IV-F2, in accordance with the Army Generic SIA Program Specification Process (see Appendix A).

The service life - design sufferance SI parameter shall be addressed throughout all of the major tasks of the materiel system SIA program. **It is especially important that design sufferance issues be understood in developing the life SIA maintenance plan as described in Task IV-F3 and the in-service usage monitoring plan described in Task IV-F4.** Design sufferance evaluation shall be made concerning *all aspects of service* life and usage, see Task I-E; for example, fatigue dominated service life, life dominated by degradation under essentially static loading conditions, or more general service life conditions.

The Army generic SIA program does not require specific identification of the percentage of the total number of each critical component which would be expected to be characterized by the base line or design sufferance parameters. The approach allows flexibility in application of these requirements in the mission specific SIA standards in recognition of the varying consequences of structural failure in diverse Army materiel systems. It is also recognized that accurate estimates of the percentages may be very difficult to achieve in view of associated technical issues particularly with regard to advanced materials.

Criteria for maximum allowable values of the measures of the design sufferance SI parameter are discussed in Task I-B6. Service life issues are discussed in Task I-D and Task II-G.

Task I-B5. Limited Duration Service Life SI Parameters - Survivability

Task I-B5a. General: Limited duration service life evaluations must be made to establish the SI of materiel systems for specified damage conditions, including survivability. The specified damage conditions are derived from the SI related materiel system operational requirements described in the SIA plan (see Task I-A). Limited duration life requirements may govern aspects of the design such as material selection and sizing, details of parts, and joining methods. The specified damage may be associated with materiel system survivability requirements (battle damage) or service damage from foreign objects. The limited duration

service life is considered in this program related to two distinct SI parameters: limited duration service life - unrepaired damage and limited duration service life - repaired damage. It should be noted that survivability requirements may also be related to full service life: unrepaired damage is to be tolerated during normal service operation or that damage resulting from large amplitude loading events should be minimized.

Task I-B5b. Limited Duration Service Life - Unrepaired Damage: Limited duration service life of a materiel system with unrepaired damage may be required for a period of a few missions or for completion of a single mission. The service life of the critical SI components shall be evaluated with regard to the specified damage. The SI aspects of the initial state of damage and subsequent growth of the damage shall be evaluated. The design loading conditions during initiation and growth of damage shall be derived from the service load analyses described in Task II-B and appropriate service life factor discussed in Task I-B7. The operational envelope permitted during limited duration life is that specified in the materiel system SIA plan (see Task I-A1). The effect of environment during the period of operation with unrepaired damage shall be assessed. The unrepaired damage SI parameter shall be addressed through all of the tasks of the SIA program. Criteria for allowable measures of the SI parameter are discussed in Task I-B6. Service life issues are discussed in Task I-D.

Task I-B5c. Limited Duration Service Life - Repaired Damage: The SI of critical parts with repaired damage shall be evaluated for the period of limited duration life required by the materiel system specifications and described in the SIA plan (see Task I-A). The design loading conditions shall be derived from the service load analyses discussed in Task II-B and appropriate service life factors discussed in Task I-B7. The operational envelope permitted during limited duration life with repaired damage is that specified in the materiel system SIA plan (see Task I-A). The effect of environment shall be considered. The limited duration SI parameter shall be addressed throughout all of the tasks of the SIA program. Criteria for allowable measures of SI parameters are discussed in Task I-B6. Service life issues are discussed in Task I-D.

Task I-B6. Criteria for Measures of SI Parameters

The evaluation of SI parameters involves resistance to maximum loading and, for various service life related SI parameters, residual strength/resistance to maximum loading. Several measures of resistance to maximum loading or residual strength may be considered. These measures include ultimate strength, yield strength, strain limit, fracture strength in the presence of a flaw or damage, and deformation related measures including buckling, creep, and loss of stiffness. The selection of appropriate measures for the SI parameters depends upon the service usage, the consequences of failure, and the failure properties of the material. For example, the traditional machine design approach is usually based on the yield strength of unflawed structure; that is, no yielding is permitted. In aviation design, the emphasis is placed on ultimate failure (strength or instability) design of structure assumed to be initially unflawed.

Coupled with the traditional measures of strength is the assumption that the structural material has sufficient toughness so that the structure is resistant to small flaws which are ignored in the design analyses. The Army generic SIA program requires a verification that the material has adequate toughness over the range of service environments to permit the use of measures of SI strength parameters which ignore flaws. For low alloy steels and some other metals, the transition temperature approach is useful, provided that the transition

temperature test specimen sizes (thickness) are adequate to represent the structural behavior of the metal for the size (thickness) of the structure in question.

For high strength metals and for structural design materials and conditions where it is not possible to verify that the materials are resistant to small flaws, an explicit flaw-based measure of the maximum loading resistance SI parameter and of residual strength for either SI parameters must be used. The strength measures should be based on linear elastic fracture mechanics (K_{Ic}) or appropriate elastic-plastic flaw-based measures and environmental effects should be accounted for by measures such as crack extension threshold for environmentally assisted crack growth (K_{IEAC}).

In view of the wide variety of Army design applications, it is not feasible to require specific measures of resistance to maximum loading SI parameters or residual strength and associated allowable strength values. The Army generic SIA program does, however, require that, where appropriate, criteria for measures of SI parameters shall be valid for combined, multiaxial loading. The measures, criteria, and associated regions of application for specific classes of materiel system designs shall be specified by the Army Generic SIA Program Specification Process, Appendix A. The process shall specify whether an ultimate strength or yield-based criterion (no yield or a specified amount of yielding) shall be applied. The "condition of structure" acceptance criteria for qualification testing (resistance to maximum loading or residual strength tests, in Task IV-A, shall be specified. The "condition of structure" specification shall indicate the amount of cracking, damage, delamination, deflection, loss of stiffness, and local buckling, if any, which is permitted associated with various design concepts such as redundancy, slow crack or damage growth, crack or damage arrest, or detection and monitoring. Such criteria must be specified for proper interpretation of qualification tests, particularly for advanced materials where widely accepted prior experience base for test interpretation is lacking. Specialized acceptance criteria may be required in certain instances such as acceptable levels of acoustic emission indications in welded structures which indicate local plastic flow and damage.

The region of application of the criterion for the measure of the SI parameters may be a point, a local region, or a global region of a structural element or subcomponent. The point-based criterion would be associated with an allowable value of a stress, strain, or energy-based quantity from continuum mechanics analyses. The local region basis for a criterion could be derived from an averaged or nominal stress, strain or energy term associated with a local geometric feature, a region of plasticity, or a region of damage in an advanced material. The global region criterion could be derived from resultant mechanics quantities associated with the boundary conditions of a structural element or subcomponent. The implementation of a global region criterion would require the generation of allowable boundary values of mechanics quantities from test data of prototype structures which represent the elements or subcomponents.

Task I-B7. Safety and Service Life Factors

Task I-B7a. Factor of Safety: The factor of safety (FOS) is chosen to account for uncertainties between the actual materiel system conditions and the SI model analysis and testing results. The FOS is a major quantitative factor associated with SI parameter analysis and test results. The FOS may account for various uncertainties and may be applied to various SI parameter measures depending upon specific aspects of the design. In machine design and general structural design, the FOS is most often used in connection with a yield stress

criterion. In aviation design, the FOS is most often used with respect to an ultimate strength criterion. In order to properly assess SI parameter analyses and test results, the factors covered by FOS should be clearly understood; in particular, the relationship between FOS and the following.

- System operation in excess of mission envelope (consistent with operation limitations described in Task I-A1 and Task IV-F3.

  Excessive loading during defined mission

  New operational mission

  System provisions to limit excessive loading

- Load uncertainties for defined missions
- Inexactness in structural model analyses
- Material variability
- Production process variability (residual stresses)
- In-service damage not specified in materiel system requirements
- Dynamic effects in lieu of rational analysis
- Temperature effects in lieu of rational analysis
- Modeling of flaws, cracks, or defects

In addition, the selection of the FOS may depend upon the consequences of failure, details of in-service monitoring and maintenance program, significance of weight penalties relative to materiel system performance, and the extent of the region of the structure for which the SI parameter is relevant (point, local, global), the methods of combined loading analysis and criteria assessment, the type of material used, and the manner in which the properties are characterized. Quantitative values of FOS appropriate for analysis and the FOS for qualification testing of each of the various measures of SI parameters shall be specified by the Army Generic SIA Program Specification Process, Appendix A. For example, for the resistance to maximum loading SI parameter, the FOS appropriate for yielding, ultimate, creep, LEFM or elastic-plastic flaw analyses for metals, or for measures applied to advanced materials, shall be specified. In addition, the FOS should be specified for residual strength analyses associated with service life and limited duration service life.

Task I-B7b. Service Life Factors: Service life factors account for uncertainties in service life analyses, testing, and qualification. The service life factors may be defined in terms of life factors related to imposed stress/strain levels or, in principle, in terms of strength factors (stress or strain) at a specified life. In fatigue dominated service life, the term "scatter factor" is commonly used to denote this factor. The service life factor may be applied also to degradation dominated service life.

The service life factor is normally expressed as a deterministic quantity. However, for helicopter dynamic components, the service life factor, on a strength basis, is usually expressed on a statistical basis of low probability of failure relative to a particular SI model.

The appropriate quantitative value of service life factor depends upon the consequences of failure and the following.

- Service life parameter: base line, design sufferance, limited life
- Life or strength based definition
- Application to analysis, testing, or qualification
- Modeling method: flaw based/nonflaw based
- Application to total life prediction/inspection intervals
- Mission spectrum: nominal/severe
- Load spectrum: nominal/severe
- Material fatigue properties
- Material properties variability
- Extent of prior data base
- Number of qualification tests
- Nominal/upper limit damage rate
- Rate of damage versus imposed loading
- Damage accumulation model approximations
- Residual stress

    Uncertainty in initial value

    Redistribution during damage process
- Modeling uncertainties
- Boundary conditions
- Local stress/strain in complex configurations and loadings
- Uncertainties concerning end of service life

    Single load path structure - definition of final failure

    Multiple load path structure - uncertainty in detection of failed path
- Failure detection system resolution
- Residual strength/resistance to maximum loading

    Difference between required residual strength at the end of service life and the residual strength at the end of typical total life test where the residual strength is zero
- Hybrid life factors

    For qualification testing of some advanced materials where the value of service life factor is based on both load level and life issues

Hybrid factors may be useful in qualification testing and related analysis for those advanced materials which during service life tests, exhibit a relatively large amount of scatter and large changes in service life associated with small changes in stress/strain level; i.e., relatively flat stress/strain versus life curve. For such materials, a very large service life factor and long test duration may be needed to provide assurance of achieving the required service life. A shorter, more practical, qualification test duration may be possible based on an enhanced load and a smaller service life factor.

Quantitative values of the service life factors for each of the service life parameters shall be specified in accordance with the Army Generic SIA Program Specification Process, Appendix A.

Task I-B8. Critical Parts List

The materiel system developer shall prepare a critical parts list. The critical parts list provides the basis for identification of those parts for which the SIA will be evaluated according to the provisions of this program.

Task I-C. Design for Structural Integrity

The Army generic SIA program requires the use of the most appropriate available technology consistent with the properties of the materials utilized and the in-service usage and maintenance. The following discussion considers designing for specific SIA parameters.

Task I-C1. Designing for Maximum Loading Resistance

The design for maximum loading resistance should be based upon approaches which are consistent with the criteria for measuring this SIA parameter as specified in the mission specific SIA standard and in Task I-B6. The details of the design configuration and the selection of materials shall be consistent with achieving necessary SIA based on the specific criteria. Thus, where appropriate, the design should take advantage of materials with favorable special properties such as fracture toughness (K_{Ic}), environmentally assisted crack growth threshold (K_{IEAC}) of metals, or specially engineered or tailored advanced materials.

Task I-C2. Designing for Service Life

The structural design shall incorporate materials, stress levels, structural configurations, and structural damage detection and monitoring systems to avoid catastrophic failure and to minimize damage initiation and growth during service. Provision for control of material degradation and corrosion prevention shall be in accordance with MIL-STD-729 and MIL-STD-735.

The design shall provide access to permit routine in-service inspections of critical structural components consistent with the manufacturing quality assurance program and qualification test evaluation (see Task IV-G). The design should also seek to minimize mandatory scheduled retirement of critical parts or components. However, detailed requirements concerning part replacement will be controlled by mission specific SIA standard or each materiel system contract.

The design, modeling, and analysis approach for service life may involve flaw or damage based methods (damage tolerant methods) or nonflaw based (safe life) methods. The Army generic SIA program requires that the design and analysis method for each critical part be

clearly identified, applied, and documented in a consistent manner throughout all of the SIA tasks.

Where feasible, the Army generic SIA program recommends the use of damage tolerant design which includes quantitative measures to assess the status of SI of critical components in service which can be utilized in the life maintenance program (see Task V-F4 and Task V-C).

Damage tolerant based design methods include:

Slow damage growth,

Multiple load paths,

Damage arrest provisions, and

In-service damage detection and monitoring.

Task I-C3. Designing for Limited Duration Service Life

The structural design approaches of the Aircraft Survivability Program, MIL-STD-2069, may be applied or adapted, where appropriate, to achieve the limited life SIA goals. The concepts and methods used for nominal service life design, as discussed in Task I-C2, should be utilized where feasible. In some materiel systems, the limited life requirements might be met by the nominal service life design and, thus, limited life SI parameters need not be considered separately.

Task I-C4. Structural Design Codes

Structural design codes are available for certain types of structures such as pressure vessels and bridges and for general construction with certain types of materials. Codes may be used to fulfill requirements of the Army generic SIA program if all aspects of the code; structural configuration and loadings, material quality, processing, fabrication and assembly, service life usage, and maintenance are consistent with the particular design application and the requirements of the Army generic SIA program. Additional measures may be required to supplement the construction code to address all major tasks required by this program.

Task I-D. Service Life SIA Plan

The Army generic SIA program requires that a service life SIA plan be prepared and implemented by all materiel system developers. The service life SIA plan shall be in accordance with the Army generic SIA program and the mission specific SIA standard and specifications. A service life SIA plan is needed to integrate the many subtasks necessary to demonstrate and document compliance with the generic SIA program. The service life SIA plan shall identify and define all tasks necessary to evaluate and achieve service life goals for the materiel system critical parts. The plan shall identify and define tasks to evaluate both service life base line design and service life design sufferance SI parameters. For some materiel systems it may be advantageous, in terms of SIA program costs and scheduling issues, to establish service life qualification only on the basis of the more severe design sufferance conditions. However, the omission of service life base line design qualification testing reduces the knowledge of the behavior of the typical unit of the materiel system, which may be undesirable with regard to non-SIA issues. The service life SIA plan shall also detail additional

tasks related to limited life conditions when design for limited life is required for the materiel system. The service life SIA plan shall include the following.

1. **Critical Parts List.** (As developed in Task I-B8.)

2. **Modeling Methods.** Identification of the design/analysis/modeling method applied to each critical part for each service life SIA parameter: damage tolerance, safe life, or new methods developed for advanced materials. It is most desirable to utilize modeling methods which are based on full field descriptions of mechanics and material property quantities valid for all points since such results are most general and easily modified to changing conditions. However, for complex configurations and for advanced materials such analyses may not be practical or feasible. The rationale for selection of the modeling methods for the service life SI parameters shall be documented in order to assure that subsequent modifications to modeling methods or materials utilized shall be consistent with appropriate modeling rationale.

3. **Life Analysis Data Development.** Definition of a program to establish quantitative data required for implementation of the design/analysis/modeling method based on mission specific SIA standard and specifications or a program for a particular materiel system. For example, damage tolerance methods for base line design require the initial flaw size related to base line initial quality.

4. **In-Service Damage.** Definition of in-service damage related to the base line design when required by the mission specific SIA standard or the materiel system specification. A definition of in-service damage related to other service life SIA parameters shall be made when necessary.

5. **Design Sufferance Issues.** Identification of conditions that are to be addressed for design sufferance evaluation. For example, if the design/analysis/modeling method identified in (b) is a flaw or damage based method, then a quantitative measure of flaw or damage size associated with design sufferance conditions should be defined. More than one design sufferance condition may be initially considered and through analysis and development testing the most critical condition would be identified and evaluated.

6. **Building Block Issues.** The plan shall describe the implementation of the "building block" approach for service life design when it is not possible to characterize on a general basis material property, geometric configuration and size effects, complex loading, and environmental effects. The plan shall identify which issues shall be evaluated, quantified, and documented by the use of coupon, element, subcomponent, and component tests.

7. **Manufacturing Quality Assurance.** Development and maintenance of a materiel procurement and manufacturing process program to minimize the possibility that initial quality is degraded below the assumed in the design. Design drawings for critical parts shall identify critical locations and special processing (e.g., surface treatments) and initial quality inspection requirements.

8. **Life Maintenance.** Development of a life structural maintenance plan consistent with the design/modeling method, the manufacturing quality assurance program, and the qualification test results. If the method is nonflaw based, the maintenance plan shall identify regions of critical parts where provisions to inhibit damage must be maintained. If the method is

flaw based, the maintenance plan must identify inspection intervals and quantitative inspection criteria.

9. **Design Trade-Offs.** Design trade-offs considering design concepts, materials, weight, system performance, and costs shall be conducted during early design phases based on evaluation of SI parameters as defined by this program.

Task I-E. Design Service Life and Usage

The materiel system operational modes and mixes of operational modes shall be realistic estimates of expected system usage. The service life modes shall include, where appropriate, storage, handling (including drop test environment for armaments), transportation and erection of structures such as bridges, and antennas. In addition, survivability operational mode shall be included for operations with unrepaired and with repaired damage when required. The specified operational modes are documented in the SIA plan, Task I-A1. The basis for the operational modes and usage shall be clearly documented to permit consistent SI parameter modeling and proper choice of FOS and service life factor (as discussed in Task I-B7). A statistical basis for mission usage may be desirable to achieve a more accurate prediction of service life SI parameters. Actual materiel system usage may differ from initial estimates. The in-service monitoring provisions of this program (see Task IV-F5 and Task V-D) provide a mechanism for feedback to documented system SI characterization for reassessment of SI parameters.

Task I-F. Materials, Processes, and Joining Methods Selection

Materials, processes, and joining methods shall be selected to achieve light weight, efficient structures consistent with the materiel system function which provide the required materiel system SIA as evaluated by the SI parameters of this program. Special emphasis should be given when considering conventional materials to materials which resist flaw or damage initiation and growth and, in general, materials which exhibit good damage tolerance, corrosion, and degradation resistance. Materials, processes, and joining methods shall be selected for prevention of corrosion and material deterioration in accordance with MIL-HDBK-729 and MIL-HDBK-735.

The rationale for selection of the materials and methods for the particular materiel system component and the supporting data base shall be documented as part of the SIA plan.

Task II. Design Analyses and Material Characterization

The objectives of the design analyses and material characterization tasks are to determine the environments in which the materiel system must operate (maximum loading, loading history, temperature, solar, chemical, etc.) and to perform analyses and characterization of materials and structures based on these environments to design and size the materiel system to meet the required strength, stiffness, and service life requirements. Subtasks of Task II may be integrated with some of the subtasks of Task III, Design Development Testing, and may be performed during the same time period.

Task II-A. Maximum Loading Analyses

The analyses shall consist of determining the magnitude and distribution of significant static and dynamic loads imposed upon the materiel system. The loadings shall be derived

from the mission requirements described by the design service life and usage (see Task I-E) and the structural design configuration. The relationship between the loading conditions being considered and the mission requirements shall be clearly identified and documented consistent with mission specific SIA standards and specifications. The loading conditions shall be identified with average or upper-bound load values associated with either normal or with extreme mission operations. All potentially critical loading conditions shall be considered arising from system operation, transportation, handling, maintenance, and storage. Loading analyses shall consider combined loads, external loads, internal (body) loads, pressure, loads from imposed displacement (including terrain), and loads from restraint of displacements produced by thermal or moisture effects. Dynamic and transient loads including blast loading shall be considered when appropriate. From such analyses the worst case maximum loading for each critical structural component shall be determined.

Task II-B. Service Load Analyses

The service load analyses shall consist of determination of significant load spectrum effects relative to the SI of the materiel system for mission operations described in design service life/usage (see Task I-E). The relationship between loading conditions and mission requirements shall be clearly identified and documented consistent with the mission specific SIA standard and specifications. The loading conditions shall be identified with average or upper-bound load values associated with either normal or extreme mission operations. All potentially critical loading conditions shall be considered arising from system operation, transportation, handling, maintenance, and storage. Loading analyses shall consider combined loads, external loads, internal (body) loads, pressure, loads from imposed displacements (including terrain), and loads from restraint of displacement produced by thermal or moisture effects. Dynamic and transient loads including blast loading shall be considered where appropriate.

From such analyses the significant load spectrum effects relative to the SI of critical parts shall be determined. If load variations are significant during service life, the service load analyses shall determine the effective service life fatigue loading. When appropriate, the service loading analyses shall determine the effective constant or slowly varying load associated with SI degradation.

The level of complexity of the analyses and the description of effective load spectra shall be consistent with the consequences of service failure of the critical part, the analysis modeling (see Task I-B and Task I-D), and the material characteristics. For example, in general, load sequence effects should be considered for inclusion in the effective load spectrum. However, load sequence effects may be omitted on the basis of previous experience with the design, analysis, and field service of specific classes of materiel system structures. The mission specific SIA standard and specification shall establish the basis for such analysis methods.

The effective service life loading would, in general, be different for each type of service life SI parameter. The operating conditions for limited life - unrepaired damage, limited life - repaired damage, and nominal service life parameters could, in general, all be different.

In addition, in some cases, unique service life - design sufferance SI parameter analysis method may be developed which should be associated with a unique design sufferance effective service life description.

In general, the service load analyses of this task and the chemical/thermal environment spectrum (see Task II-C) may be combined to describe an effective service load and environment for the critical structural parts of the materiel system.

Task II-C. Design Environment

The design environment imposed on each critical component shall be established based on the design service and usage (see Task I-E). The environment shall include chemical, thermal, moisture, solar, and nuclear effects when appropriate relative to the structural material. The intensity, duration, and frequency of occurrence of each environment shall be established. The relevant environment shall be established with respect to each of the SI parameters such as maximum loading, service life - base line design, service life - design sufferance, and limited duration service life - unrepaired and repaired damage. Environmental effects should be assessed for limited duration SI parameters, despite the short service period under consideration, since damage in certain materials may destroy environmental inhibiting provisions and cause severe degradation in a short time period. The environment for service life - design sufferance SI parameters may be substantially different from the environment for the base line SI parameter if the deviation from base line combination involves loss of environmental inhibitors.

The analysis of thermal distributions shall be with sufficient detail to be consistent with failure models. If special design features are employed to inhibit environmental effects, appropriate maintenance provisions to retain these features shall be established and documented in the structural maintenance plan described in Task IV-F.

Task II-D. Material Property Characterization

Task II-D1. General

Material properties shall be selected or developed which are most appropriate for the structural material, the critical component design detail, design service environment and usage, and the design/analysis/testing modeling method. Material properties and material allowables may be obtained from MIL-HDBK-5 and MIL-HDBK-17. Selection and development of material properties and allowables from additional sources shall be in accordance with the mission specific SIA standards and specifications. Material properties for SIA shall include material allowables (see Task II-D2), stress-strain curves, elastic constants, fatigue crack or damage growth rates, fatigue crack or damage thresholds, stress or strain fatigue life curves (S-N curves), environmental crack growth data, environmental crack growth thresholds, and creep growth curves. The design service environment, including temperature, humidity, corrosive media, solar, and nuclear radiation shall be as determined in Task II-C. Material properties shall be obtained for all orientations of anisotropic materials which may be of significance relative to SI. Property data shall be obtained at time rates consistent with service conditions of the critical component. Dynamic service conditions may involve impact loading, or inertial launch loading, or high dynamic blast loading conditions. If dynamic material properties are obtained by methods which do not involve the dynamic regime directly, the rationale and supporting data shall be documented in the mechanical properties summary (see Task II-D3).

Material properties or allowables shall be characterized with respect to repeated or reversed loading conditions when appropriate. Reversed loading may influence allowables in metals if local plastic flow occurs under initial loading. The yield strength under reversed

loading may be substantially reduced (Bauchinger effect). Material allowables, elastic-plastic failure, and ultimate strength may also be significantly affected by repeated or reversed loading. Examples of reversed loading are: ballistic missile launch and reentry loading, and regions in a projectile which are initially subjected to large compressive loading in the gun tube followed by a sudden removal of gun barrel restraint which produces tensile stresses when the projectile leaves the gun.

Task II-D2. Material Allowables

The basis for the material allowables shall be identified and documented to substantiate application to the particular class of design. The basis shall be in accordance with the mission specific SIA standard and specification.

Task II-D2a. Metals: The basis for strength allowable for general metallic structures and machine design is typically the yield stress. For aeronautical systems, material allowables are typically based on ultimate strength or ultimate buckling resistance. Allowable values for fracture properties, such as K_{Ic} or J_{Ic}, which may be important relative to SI are defined by the applicable standard test procedure. Additional material allowable properties may be associated with evaluating SI which are not used directly in computational models. Examples of such properties are transition temperature criteria for material toughness as measured by Charpy specimen tests and material ductility criteria as measured by tensile specimen elongation or reduction in area at fracture. When such properties are used to control critical component part SI, the basis for the allowable shall be documented in the Materiel System Mechanical Property Summary. For example, the required Charpy value may be based on a transition temperature criterion or based on an empirical correlation with previous service experience for certain types of critical components in certain materiel systems.

Strength allowables for welded structures which are subjected to repeated loading shall be based on data for large scale structures rather than typical small scale laboratory type specimen data. Strength allowables for fatigue-loaded welded structures with specific configurations and associated welding practices are available from the American Institute of Steel Construction (AISC), the Aluminum Association, and the American Association of State Highway and Transportation Officials on Bridges and Structures (AASHTOBS).

Task II-D2b. Composite Materials: Composite material properties shall be obtained on a statistical basis (see Task II-D2f). Design allowables for specific structural features may be identified with specific associated structural behavior such as maximum loading resistance or service life after impact, or associated with delamination behavior, or at specified regions of stress or strain concentration. Composite material property basis values are obtained from unidirectional lamina specimens.

Task II-D2c. Brittle/Ceramic Materials: *Allowable values shall document associated specimen* type and size and shall be expressed in statistical terms (see Task II-D2f).

Task II-D2d. Service Life (Fatigue): Allowable fatigue strength values shall document the specimen type and size and extent of life associated with the allowable values. Particular attention should be given to size effects to ensure the material fatigue allowables are valid for the full section sizes of critical parts. The size effect should be verified by service life design-development testing, as discussed in Task III-E, when necessary. Allowable strength values may be associated with a defined specific period of life or under limited circumstances for

an infinite life; i.e., an endurance limit for steels and some other metals. The endurance limit is displayed only for essentially steady state loading of steels, but for general spectra, no endurance limit exists for variable loading of steels or other metals. Allowable fatigue strength values obtained during development of a material system through the building block method (see Task III-C) shall be documented in this summary. If results may be expressed in statistical terms, refer to Task II-D2f.

Task II-D2e. General Design Codes: Material allowables may be obtained from general design codes such as the ASME Pressure Vessel Code or the AISC Structural Code provided that it is documented that all related SI issues (see Task I-C4 and Task II-D1) of the materiel system design are consistent with the associated conditions for which the code is applicable.

Task II-D2f. Statistical Basis: Material allowable and design allowable values for advanced materials, composites and ceramics, are best described on a statistical basis such as an A or B basis. A and B basis statistical methods are described in MIL-HDBK-17. Polymeric matrix composites shall be characterized by statistical methods in accordance with MIL-HDBK-17.

Task II-D3. Material Properties Summary

A materiel system material properties summary shall be prepared by the materiel system developer which includes the appropriate material properties and related data cited in Task II-D1 and Task II-D2. In addition, the summary shall include the appropriate portions of the information relating to each of the material property data such as material composition, impurity level control, processing, fabrication, and special quality assurance measures necessary to maintain special features such as environmental resistance and statistical basis.

Task II-E. Mechanics Analyses

The mechanics analyses shall determine static and dynamic stresses, strains, and deformations resulting from imposed mechanical and environmentally induced loads (see Task II-A) necessary to perform failure analyses (see Task II-F) of critical parts. The modeling shall consider appropriate regions (point, local, and global) and associated failure criteria (yielding, local fracture, global failure, or buckling as discussed in Task I-B6). The mechanics analyses methods shall be in accordance with structural integrity characterization (see Task I-B, in particular, Task I-B6), and the mission specific SIA standard and specifications. When necessary, the analyses shall consider loading resulting from dynamic, transient, or vibratory motion of a structure. Transient or vibratory motion analyses of a structure may be used to tailor structural response in addition to its application to SI evaluations.

Mechanics analyses shall include residual stresses when such stresses are intentionally introduced as in the controlled yielding of autofrettaged gun tubes. If residual stresses of unknown magnitude are thought to exist in critical structures, such stresses should be conservatively approximated. Residual stresses from processing and fabrication may occur, for example, in forming closed complex shapes such as missile cases and in unstress relieved welded joints. Approximate residual stress analyses should be validated or modified by results from design development testing.

The mechanics analyses shall be used to assess the maximum loading resistance of a structure and for service life analyses. The mechanics analyses shall be used as guidance for selecting critical structural components for design development testing (see Task III) and for early design review actions. The mechanics analyses are a major factor in the determination of imposed loading distributions in qualification testing (see Task IV).

The Army generic SIA program requires that mechanics analyses shall be documented in a manner which is suitable for subsequent use in design development and qualification testing, and for modification to assess effects of design changes and life management issues including mission changes and life extension programs. The mechanics analysis of complex configurations for both conventional and advanced materials may require supplemental experimental data. Design development test data may be needed for joints in both conventional and advanced materials (see Task III-B) and for various configurations of advanced materials where design data is obtained through building block testing (see Task III-C). If analyses are to be modified or supplemented by test data related to combined classical-empirical methods, special care should be taken to adequately document the analyses consistent with the needs of the materiel system SIA program.

Task II-F. Structural Integrity Analyses at Maximum Loading

Maximum loading resistance is typically the principal structural integrity requirement for materiel systems such as projectiles and missiles where launch loading is likely to be the dominant SI issue. The maximum loading resistance is a SI requirement for all materiel systems, and it is an important design benchmark which can be verified in the design development process before service life SI parameters are completely evaluated.

The maximum strength resistance of structures is the loading criteria which is most appropriate for many structural configurations, but stiffness/buckling criteria may be the most appropriate for light weight shell structures of the kind which might be utilized in missile skins or a helicopter fuselage.

The resistance to maximum loading SI parameter analyses shall be obtained for all critical components for all potentially critical loading conditions including combined loadings. Analyses shall be based on the following issues in accordance with the provisions of this program:

- Mechanics analyses (see Task II-E),
- Safety factors (see Task I-B7),
- Materials properties and allowables (see Task II-D), and
- Design/development testing data (see Task III-B, Task III-C, and Task III-D).

Structural design codes may be used to evaluate the maximum loading resistance SI parameter provided that the requirements cited in Task I-C4, Task II-D2e, and the mission specific SIA standard and specifications are satisfied.

The degradation of critical part strength and stiffness due to environmental exposure should be assessed in the service life evaluations in Task II-G and Task II-H.

The Army generic SIA program requires that the analyses of the maximum loading resistance SI parameter shall be documented in the final analysis summary (see Task IV-F2) in a

manner which is suitable for subsequent use in design, development, and qualification testing, for use in assessing effects of design changes, and for life management issues (see Task V), including mission changes and life extension programs. The maximum loading SI parameter analyses shall be approved by the responsible Army organization.

Task II-G. Service Life Analyses

Task II-G1. General

Service life prediction analyses are required for all potentially critical locations of critical structural components for all service loading conditions and histories. For Army systems such as aeronautical systems, surface vehicles, bridging, and antenna structures, the dominant service life issue is fatigue. In addition, for some systems such as aeronautical systems, the dominant fatigue life issue may be related to limited life parameters. For other Army systems such as missiles and projectiles, important service life issues are degradation in strength or stiffness from environmental effects and the potential of damage from transportation and handling. The Army generic SIA program requires service life predictions for all service life SI parameters in order to substantiate the SI for the design lifetime. The analyses shall be approved by the responsible Army organization.

The service life analyses serve as a benchmark for initial assessment of the adequacy of the structural design in the service environment. In addition, the analyses form the basis of a permanent, updated, validated documentation which will be available for future actions in life management (see Task V). The analyses may be subsequently modified to reflect the results of design development and qualification testing. It is desireable that the analyses should be developed on fundamental principles rather than an empirical basis, to the extent feasible, in order to be more suitable for modification.

Modeling methods shall be consistent with the service life SIA plan (see Task I-D). Different modeling methods may, by necessity, be applied to different critical locations within a materiel system, but, in general, uniformity of modeling is desirable to the extent feasible.

Service life SI parameter predictions shall be obtained for base line and design sufferance conditions for both total life and for inspection intervals.

Material behavior, loading, and structural configuration complexities may be such that it is necessary to rely on specific material, loading, environmental, and configuration dependent results of building block testing (see Task III-C) to obtain base line and design sufferance service life predictions. Service life analyses methods and test data interpretation shall be in accordance with procedures specified by the Army Generic SIA Program Specification Process, Appendix A. All of the service life SI parameter analyses shall be approved by the responsible Army organization.

Task II-G1a. Service Life Factors: The service life factors used in connection with analysis and testing of service life SI parameters shall be selected on the basis of issues cited in Task I-B7b in accordance with the Army Generic SIA Program Specification Process, Appendix A and documented in the final analysis summary (see Task IV-F2). If hybrid methods are used to account for variabilities related to the service life SI parameters which involve both time and load/strain quantities, it must be demonstrated by design development testing (see Task III) that increased load/strain does not introduce new failure modes in critical structures.

Task II-G1b. Residual Strength: The evaluation of service life SI parameters requires the specification of the associated residual strength capability of the structure throughout the specified life period. In general, the required residual strength should be such that the structure could resist the maximum nominal load or the maximum nominal load multiplied by a factor of safety. A residual strength based on a load less than the maximum nominal load may be justified in certain cases. The appropriate requirement for residual strength depends upon the consequences of failure of a critical part and the following issues.

- Load/stress spectrum

  Average/severe basis

- Factor of safety

  General value specified in Task I-B7/particular value for residual strength

- Modeling method

  Flaw based/nonflaw based

- Structural design concept

  Slow crack growth

  Leak before break

  Crack arrest

  Multiple or redundant load path

  Damage containment

  Damage detection

- Material allowable basis
- Inspection interval and method

Residual strength requirements for each type of service life SI parameter shall be specified in accordance with the Army Generic SIA Program Specification Process, Appendix A. Supporting rationale and data shall be documented in the final SI analysis summary (see Task IV-F2).

Task II-G1c. Environment: Environmental effects shall be included in all service life SI parameter predictions. Environmental effects shall be considered in both fatigue-dominated service life and service life predictions where the dominant issue is degradation of maximum loading resistance SI parameter. Environmental effects to be considered include temperature, humidity, corrosive media, solar radiation, and nuclear effects.

For some designs, particularly using advanced or novel materials, the material properties characterization related to environmental effects may be incomplete. Acceptable empirical methods to account for environmental effects in service life SI parameter analyses for specific combinations of service life SI parameter, environment, material, modeling method, and design concept shall be specified by the Army Generic SIA Program Specification Process, Appendix A.

Task II-G2. Service Life - Base Line Design Analyses

The service life - base line SI parameter evaluation is related to service life or inspection interval periods which represent the behavior of critical components with respect to nominal design conditions. The service life - base line SI parameter shall be evaluated analytically for all potentially critical locations based on results of mechanics analyses (see Task II-E) or prior experience with similar structural configurations and materials. The generic SIA program permits flexibility in choosing modeling methods in view of the wide variety of Army materiel systems.

Task II-G2a. Flaw Based Analysis: The flaw or damage based analysis shall consider the following.

- Flaw or damage growth model: load spectrum and interaction effects, multiaxial effects
- Initial quality flaw or damage size
- Service load analysis: Task II-B
- Chemical/environmental spectrum consistent with flaw/damage growth model: Task II-C
- Stress analysis consistent with region of modeling: Task I-B6
- Redistribution of stresses during flaw/damage growth
- Residual stresses

Material Properties: Task II-D

- Consistent with region of modeling: data from design/development tests (see Task III) for structural region
- Growth rate model
- Growth threshold model
- Material variability

Design Development Tests

- Loading/material/environment/configuration dependent tests (building block approach)
- Size effects
- Environmental effects

Definition of "End of Life Event"

- Failure: fracture, loss of stiffness, buckling
- Residual strength: Task II-G1b
- Damage containment
- Damage arrest
- Damage detection by monitoring system

- Multiple load path behavior

  Detection of failure in one path

  Continuing damage in unfailed paths

- Leak before break

Service life scatter factor: Task I-B7b, Task II-G1a

Statistical failure basis

The initial quality flaw or damage size for service life base line SI parameter analysis shall be specified by the mission specific SIA standards and specifications for specific classes of design configurations. The rationale for initial quality flaw/damage specifications shall be documented in the mission specific standards and specifications with reference to the following issues: material composition, form, processing, manufacturing methods, fabrication and assembly methods, inspection methods, accessibility for inspection, and design configuration and concept (slow growth, redundant load path). If the initial quality flaw/damage size for service life base line parameter analysis for conditions relating to a particular materiel system has not been specified by the mission specific SIA standards and specifications, the materiel system developer shall determine the initial quality value based on issues cited in this section. The supporting basis for the initial quality determination shall be documented in the SI analysis summary (see Task IV-F2).

Task II-G2b. Nonflaw Based Analysis: Nonflaw based analyses, such as safe life analyses, shall consider the following.

Damage Accumulation Model:

- Load spectrum and interaction effects
- Multiaxial/multimode effects

Service Load Analysis: Task II-B (consistent with damage accumulation model)

Chemical/Environment Spectrum: Task II-C

Stress/Strain Analyses

- Mechanics analyses: Task II-E (where appropriate consistent with region of modeling - Task I-B6)
- Residual stress

Material Properties/Allowables: Task II-D

- Finite life versus stress/strain/load
- Endurance strength/strain limit: infinite life
- Size effect: specimen/structural
- Environment

- Fretting
- Surface condition
- Mean stress/residual stress effect
- Stress concentrations

  Notch sensitivity

  Fatigue reduction factors
- Material variability

  Statistical basis including A or B basis

Design Development: Subcomponent Tests

- Loading/material/environment/configuration dependent tests building block approach
- Size effects
- Environmental effects

Definition of "End of Life Event"

- Defined by damage accumulation model
- Multiple load path behavior

  Detection of failure in one path

  Continuing damage in unfailed paths
- Failure detection monitoring
- Statistical failure basis

Service Life (Scatter) Factor: Task I-B7b and Task II-G1a

- Finite life basis
- Strength basis (defined life including infinite life)
- Life/strength hybrid basis
- Statistical failure basis

The damage accumulation model, building block testing methods, and the definition of the end of life and service life (scatter) factors shall be in accordance with the mission specific SIA standards and specifications, and the basis and rationale shall be documented in the SI analysis summary (see Task IV-F).

Task II-G2c. Maximum Loading Resistance In-Service Degradation: The service life - base line SI parameter shall be evaluated for degradation in maximum loading resistance for structures which have no repeated load design requirements. Missiles and armaments systems may be of this category. The evaluation of maximum loading resistance during service life shall be based on the environmental spectrum - temperature, humidity, chemical, solar energy,

and nuclear effects (see Task II-C), mechanics analysis (see Task II-E and Task I-B6) including residual stresses, material properties (see Task II-D), and a damage accumulation model. The analyses shall consider, where appropriate, redistribution of residual stresses due to discrete flaw or damage growth or due to relaxation and creep behavior. The damage accumulation model shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A, for the material, environment, and stress distribution conditions. The rationale and basis for the selection of the degradation growth or damage accumulation model and the design environment shall be documented in the analysis in the SI analysis summary (see Task IV-F).

Task II-G3. Service Life Design Sufferance Analyses

The service life - design sufferance SI parameter shall be evaluated by analytical predictions of service life period or inspection interval. Design sufferance conditions must be evaluated for each potentially critical part or component. Service life - design sufferance approach is discussed in structural integrity characterization, Task I-B3 and Task I-B4. The design sufferance conditions may occur in some of the total number of each critical component and produce accompanying significant reductions in the structural integrity of a materiel system.

The generic SIA program permits flexibility in developing methods which can be useful in evaluating the effect of design sufferance upon service life. The Army generic program does not limit methods, as in the case of the Air Force MIL-STD-1530A, which requires damage tolerance, flaw based methods, with specified initial quality flaw sizes. The major emphasis of the Army generic SIA program, design sufferance analysis, is directed toward local issues in contrast to uncertainties which are expressed in global terms such as material property variations, modeling uncertainties, or general effect of excessive loading conditions which are traditionally accounted for by specification of factor of safety or limiting statistical behavior of "nominal quality" structure. However, the Army generic SIA program permits the application of any method, local or globally based, which can be demonstrated to be effective in addressing the design sufferance concerns related to structural integrity.

In developing the most appropriate design sufferance conditions related to a particular class of materiel system, the following issues shall be considered.

- Materiel system design configuration and service use
- Service life - base line SI parameter modeling methods
- Material manufacturing (methods and processes, fabrication, and assembly), size and complexity of critical structure, initial quality and in-service quality assurance maintenance monitoring programs, and the consequences of failure and issues cited in Task I-B4.

A design sufferance issue which may be of importance is the occurrence of "rogue" flaws or damage in metallic or advanced structures. Experience with large materiel system structures indicates that unusually large flaws or damage can occur initially or in service on a statistically infrequent basis. Another potentially important design sufferance issue is the effect of relatively small flaws in highly stressed structures, including flaws in buckling critical structures which are modeled by nonflaw based methods (safe life) in service life - base line analysis. Additional potential design sufferance conditions are unintended out-of-plane loading which may activate new failure modes in advanced materials, damage of advanced materials in

service or in maintenance, in-service loss of near surface conditions which inhibit fatigue initiation and growth (such as favorable residual stresses), loss of environmental protection of metallic or advanced materials by in-service or in-maintenance damage, or by excessive mechanical or environmental loading in service. The effect of the interaction of multiple flaw or damage sites may be considered as a design sufferance condition if such behavior is not considered in the base line analysis.

Important design sufferance conditions related to degradation in material systems where resistance to maximum loading is the dominant SI issue may be flaws or damage resulting from rough handling or drop testing, loss of environmental protection due to damage in handling, maintenance, or storage, to excessive mechanical or environmental loading including unexpected corrosive media.

The service life - design sufferance SI parameter evaluation shall consider the issues which were cited relative to the base line evaluations in Task II-G2. The analysis methods and documentation shall be based on fundamental principles, to the extent feasible, minimizing empirical bases, in order to be most suitable for modifications and for implementation of the life management program (see Task V). The service life design sufferance SI parameter evaluation shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A. The rationale and basis for selection of design sufferance issues and methods shall be documented in the SI analysis summary (see Task IV-F2).

Task II-H. Limited Duration Service Life Analyses (Survivability)

Task II-H1. General

Limited duration service life SI parameter analyses deal with materiel system conditions which arise from in-service damage defined by the materiel system specifications and which are included in the SIA plan (see Task I-A). The limited duration service life - unrepaired and repaired damage SI parameters are discussed in structural integrity characterization (see Task I-B5). The limited life SI parameter analyses shall consider the service life issues cited for base line analysis (see Task II-G2). The limited duration service life SI parameter analysis methods and criteria shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A. The rationale and basis for selection of limited duration SI parameter issues and methods shall be documented in the SI analysis summary (see Task IV-F2).

Task II-H2. Limited Duration Service Life - Unrepaired Damage

The mission spectrum (see Task I-E) may be less severe than the service life base line SI parameter spectrum. The focus of the analysis is aimed at flaw or damage growth, arrest, or containment. Explicit flaw or damage modeling methods are desireable. The analysis of advanced material structure may require utilizing the building block approach (see Task III-C).

Task II-H3. Limited Duration Service Life - Repaired Damage

The mission spectrum (see Task I-E) may differ from the service life base line and limited duration service life - unrepaired damage spectra if operational restrictions are associated with system operation with repaired damage. Such operational restrictions described in the materiel system specification and included in the SIA plan (see Task I-A) should also be

described in the life management data package (see Task IV-F). The analyses are primarily concerned with the repair structure and joint regions of the nominal structure.

Task III. Design Development Testing

Design development testing is a major task which supplements analytical tasks in developing structures for qualification testing (see Task IV). Design development subtasks may be integrated with design analysis and material characterization subtasks (see Task II) and may be performed during the same time period as portions of Task II. Design development testing may be conducted for the following objectives:

(a) Determine refined details of imposed conditions, mechanical and environmental loading, and loading rate resulting from defined mission operating conditions, Task I-E, and which are analyzed in Task II-A, Task II-B, and Task II-C.

(b) To assure the suitability of design concept in achieving SI goals.

(c) Identification of failure modes or verification of failure modes as considered in Task I-B6, Task II-F, Task II-G, and Task II-H.

(d) Determine flaw/damage initiation and growth behavior in regions of complex loading and geometry.

(e) To validate stress analyses; to evaluate effect of actual physical boundary conditions, residual stresses, complex loading, and configuration.

(f) Implementation of the building block approach for SI design and evaluation of advanced materials.

(g) Validate damage accumulation models for complex loading spectra related to service life SI parameter evaluations.

(h) Assess potential service life - design sufferance SI parameter issues and to assist in selection of most critical design sufferance conditions for qualification testing.

The results of design development testing which validate analytical models should be expressed on fundamental bases, minimizing empirical bases to the extent feasible, in order to clarify the rationale supporting the documented analyses and to facilitate future modifications to the analyses which may be necessary on the basis of new data from in-service monitoring and inspections (see Task V). Design development testing should be integrated with analysis modeling through careful instrumentation of strain, displacement, deflection, flaw or damage growth, acceleration, temperature, and nondestructive evaluations (NDE) to assist in the interpretation and validation of analytical models.

Task III-A. Service Loading and Environmental Development Testing

Design development tests of subcomponents, components, or models of such components may be required to improve understanding of design loading and environmental conditions related to SI parameter evaluations of materiel systems. For example, wind tunnel testing may be required to determine loading and structural displacement behavior of airborne systems or large antennas. Test of thermal environment may be required for materiel systems

with complex thermal effects and gradients to establish thermal stress and deformation effects or to improve definition of environment for evaluation of appropriate material properties. Also, structural testing may be required to fully understand issues for proper modeling of systems subjected to highly dynamic loading, which may undergo large displacement or deflections. Testing of full scale materiel systems shall be conducted to verify loading and environmental conditions and structural response when necessary. Design development service load testing may be required to validate the effective load spectrum or sequence relative to particular material environment, local structural complexity and associated modeling methods (flaw damaged based or nonflaw based). Service loading and environmental testing shall be in accordance with the mission specific SIA standards and specifications.

Task III-B. Joints - Mechanical Testing

Design development testing for the evaluation of structural joints should be given major emphasis for all SI parameters when joints are present in the design. Joint behavior is often the limiting factor in achieving efficient, lightweight structural designs. This critical behavior results, in part, from high stresses and strains in regions of localized concentrations and, in part, from the influence of local material conditions or "quality," or the presence of flaws or damage. Joints may be connected by bolts, rivets, pins, threads, or bonded, welded, brazed by mechanical interference, or by combinations of the basic types.

Joints design for metallic aerospace structures shall be in accordance with MIL-HDBK-5 where applicable.

Task III-C. Building Block Testing - Advanced Materials

Design development testing is the primary task related to implementation of the building block approach for structural design with advanced materials. Building block testing refers to the process of developing structural design information through a series of tests of increasing complexity such as coupons, elements, subcomponents, and components. Since general methods for rational evaluation of all pertinent issues of failure mode, configuration effects, environmental effects, and statistical description of parameters may not be possible for advanced materials, a series of limited purpose tests is performed to investigate particular issues with particular test configurations. Through proper interpretation of each type of test data or building block, including a limited number of tests of full scale structure, the SI of the materiel system can be characterized by consideration of all appropriate design issues. These tests shall be consistent with the service life SI parameter modeling, the service life SIA plan (Task I-D), the maximum loading resistance modeling (Task II-F), and shall be in accordance with the Army Generic Program Specification Process, Appendix A.

The test configuration shall be such that features which have the most critical influences on the Si of advanced materials are evaluated such as stress/strain concentration behavior, behavior after foreign object impact, and damage/delamination growth. A sufficient number of structures shall be tested to permit a statistically significant interpretation of test data. The statistical basis, such as A or B allowables, shall be specified according to the Army Generic SIA Program Specification Process, Appendix A.

The rationale for the building block test interpretation shall be documented in the SI analysis summary described in Task IV-F2. The documentation shall identify the rationale for selection of criteria for design for maximum loading resistance SI parameters and for service

life SI parameters and the allowable values for design with reference to: loading (tension, compression, shear, bending, fatigue), loading rate, size effects, and environment (temperature, humidity, and solar energy).

Task III-D. Maximum Loading Resistance

Maximum loading resistance design development tests are conducted to assess design concepts and to provide opportunity for early assessment of failure mode assumptions of analytical models for both maximum loading resistance and service life SI parameters. For example, these tests may assess the crack or damage arrest or containment capability of a design including performance of redundant load path structure. Maximum loading resistance tests should be conducted to assess the SI of regions of complex structural configuration and loading, uncertain physical boundary conditions, and influence of internal (residual) stresses and strains. These tests should be carefully instrumented, consistent with analytical models, to validate analytical models and to investigate regions of damage initiation and growth. Instrumentation should be devised to provide data to validate analytical modeling and for detailed assessment of SI within regions which are not analyzed in detail. For example, if an analytical model is based on global quantities, then the design development test instrumentation within the region not modeled analytically provides the only detailed measure of SI behavior within the region. The instrumentation must be sufficiently detailed to adequately characterize potentially critical SI behavior within the region. Maximum loading resistance tests shall be conducted at loading rates which simulate in-service loading rates unless it can be shown by analysis or an appropriate data base that the structural response to the loading rate is essentially a static response. Interpretation of such tests should account for dynamic material property or allowable behavior in the imposed dynamic regime.

Task III-E. Service Life - Base Line Design

Service life design development tests are conducted to assess the suitability of design concepts to achieve materiel system life and residual strength requirements.

Service life tests for fatigue dominated service should be conducted using loading spectra which effectively represent the actual stress/strain spectra under complex loading for regions of complex configuration and uncertain loading conditions in critical parts. The tests shall obtain data consistent with the design, analysis, and modeling methods as outlined in the service life SIA plan, as discussed in Task I-D and Task II-G2. The results may be in terms of residual strength of flawed or damaged material, or in terms of fatigue strength of material which is modeled as nonflawed material.

Development tests assess the suitability of analytical modeling and the validity of damage accumulation models for complex loading spectra. Service life designs using advanced materials and some design using metals must be based on statistical measures consistent with the service life SIA plan, discussed in Task I-D. Tests to support such design must be of sufficient quantity to produce statistically significant results. The basis for statistically significant results shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A, and shall be documented in the SI analysis summary (see Task IV-E).

In principle, service life base line design development tests for degradation should be addressed in this subtask. However, the degradation phenomena may occur over very long time periods. An accelerated test would be useful if its validity can be shown. If an

accelerated test method is used, it shall be in accordance with the Generic Program Specification Process, Appendix A. Design development test results relating to service life - base line SI parameter evaluation shall be documented in the SI analysis summary (see Task IV-F2), including validation of modeling and analysis methods, results of building block testing (such as stress/strain data for environmental conditions or for local geometry effects for correlation with qualification tests), statistical basis data, and accelerated test results.

Task III-F. Service Life - Design Sufferance

Design development testing to support service life design sufferance SI parameter evaluation should assess the suitability of SI characterization approach for the materiel system design, particularly if the approach is essentially empirical. Design development testing can be useful in assessing the most critical design sufferance issues from several candidate issues for qualification test evaluation. Design development testing should assess the suitability of design concepts, validation of analytical modeling, and failure modes using precision instrumentation of the most appropriate regions as stated in discussion related to base line design. Design sufferance development testing may involve design conditions, modeling, and qualification methods which may differ substantially from methods used in relation to the base line design. Design development testing for service life design sufferance SI parameters shall be consistent with service life SIA plan (see Task I-D) and analysis and modeling development in Task II-G3.

The design sufferance issues to be evaluated may include the following.

- Unusually large rogue flaws in flaw based models
- Small flaws in nonflaw based models
- Effect of flaws on buckling or structural stiffness
- Effect of unintended out-of-plane loading of advanced tailored structures not included in base line design
- Loss of surface conditions which inhibit damage formation

    Favorable residual stress

    Environmental protection

- Multiple site/crack or damage interaction/wide scale damage
- Exceeding mission loading
- Excessive environmental conditions, temperature/moisture/solar and nuclear effects

Design development test results relating to service life - design sufferance SI parameter evaluation shall be documented in the SI analysis summary (see Task IV-F2), including evaluation of the most critical design sufferance issues, validation of modeling and analysis methods, results of building block testing (such as stress/strain data for environmental conditions or for local geometry effects for correlation with qualification tests), and statistical basis data.

Task III-G. Limited Duration Service Life

Task III-G1. Unrepaired Damage

Design development tests of critical structure subjected to specified in-service damage under the specified limited duration service life - unrepaired damage spectrum shall be conducted to assess design concepts, to validate analyses and modeling methods, and to assess failure modes using appropriate instrumentation based on the consideration of the issues of design development testing stated in the discussion of base line design testing. Results shall be documented in SI analysis summary (see Task IV-F), as necessary (see Task III-E).

Task III-G2. Repaired Damage

Design development tests using the specified spectrum for limited duration service life - repaired damage shall be conducted to assess issues and using instrumentation methods as stated previously. Results shall be documented in the Si analysis summary described in Task IV-F, as necessary (see Task III-E).

Task III-H. Manufacturing Methods and Quality Control Prequalification Test Summary

The Army generic SIA program requires that a manufacturing method and quality control prequalification test summary be prepared by the materiel system developer. The summary shall include all quality control issues which influence the SIA of the structure which is to be qualification tested (see Task IV). The summary shall be referred to design drawings of critical parts and shall include procurement, manufacturing and process specifications, and complete nondestructive testing requirements. The summary shall identify the relationship between specific critical manufacturing methods, quality insurance provisions, and the associated SI modeling and qualification testing program, where appropriate. For example, in order to achieve the required service life of metallic structures, it may be necessary to control inclusion, porosity, and imperfections to specific size requirements through nondestructive inspection methods. If proof tests are considered for initial or in-service quality control, the associated structural effects throughout the entire structure shall be evaluated; in particular, the potential for detrimental effects of inelastic deformation or damage initiation upon subsequent SIA. The summary shall identify areas of critical parts where special processing is utilized to promote SIA such as nitriding, shot peening, or environmentally protective coatings.

Task IV. Qualification Tests and Life Management Data

Qualification tests are a major task in the evaluation of the SI of a materiel system. This task also includes the documentation which characterizes the SI of the materiel system and describes the necessary structural maintenance measures in the life maintenance plan to assure that structural integrity is maintained in service.

Task IV-A. Maximum Loading Resistance Tests

Task IV-A1. Structure

The Army generic SIA program requires that the maximum loading resistance qualification testing shall test fully assembled structures with the configuration of the materiel system to the extent that is practical. Qualification testing of such a configuration is intended to permit qualification of the entire structure where critical parts are assembled and loaded as they

would be in the materiel system in service. In addition, structural damage or failure of parts or regions or parts which may not have been predicted by SI analyses at maximum loading (see Task II-F) or by design development testing (see Task III) can be detected and evaluated. The fully assembled structural details shall be in accordance with those specified by the Army Generic SIA Program Specification Process, Appendix A. If the analysis modeling method is flaw or damage based, the test structure shall contain initial quality flaw or damage sizes in the most critical locations.

Task IV-A2. Number of Tests

The number of tests necessary to evaluate the maximum loading resistance SI parameter depends upon material variability, design concepts (redundant, containment, leak before break, or damage detection system), the criteria for measurement of this SI parameter, the factor of safety, the consequences of failure, the historical data base of similar materiel system designs and in-service usage, and data from design development testing (see Task III). A single test or a number of empirically based or statistically based duplicate tests may be necessary. The number of tests required shall be specified by the Army Generic SIA Program Specification Process, Appendix A.

Task IV-A3. Loading and Environment

The test loading shall consist of direct application of actual loading distribution, including complex loadings and loading rate. The loading distributions shall be those determined in the maximum loading analysis (see Task II-A). For materiel systems such as missiles and projectiles, the actual loading distributions and rate may be directly applied by firing tests. However, firing tests also require consideration of simulation issues related to accounting for environmental effects such as temperature, corrosive media, hydrothermal, solar energy, and nuclear environments.

Qualification tests shall account for the dynamic effects produced by the dynamic loads identified in the maximum loading analyses (see Task II-A). The effects shall be accounted for either by direct dynamic testing or by simulation of the dynamic loading condition effects. The simulation of dynamic loading effects shall consider both the dynamic structural response and the material behavior under dynamic loading. Acceptable methods to account for dynamic structural response can be assessed from results of mechanics analyses (see Task II-E), design development testing, and from a historical data base of SI of similar structures. Either an appropriate dynamic load or a static load adjustment such as a load enhancement, must be applied. If a load enhancement method is used, the qualification test damage or failure modes must be the same as in material property or allowable tests or design development tests on which the SI analysis at maximum loading (see Task II-F) is based. Qualification testing for dynamic effects shall be in accordance with specifications from the Army Generic Program SIA Specification Process, Appendix A.

Qualification tests shall account for environmental effects consistent with the design environment analyses (see Task II-C) and environmental testing (see Task III-A). Environmental effects shall be produced either by direct environmental testing or preconditioning, load enhancement (derived from material property environmental "knockdown factors"), or by correlation with design development environmental test data on the basis of a relevant mechanics parameter. If the load enhancement approach is used, the damage and failure modes must be the same as in material property or allowable tests, or design development tests, on which

the SI analysis at maximum loading (see Task II-F) is based. Qualification testing for environmental effects shall be in accordance with specifications from the Generic Program SIA Specification Process, Appendix A.

The magnitude of qualification test loading shall be the sum of the levels derived from the maximum load analysis (see Task II-A), the factor of safety for qualification testing for maximum loading resistance SI parameter (see Task I-B7), and load enhancements associated with the simulation of dynamic and environmental effects. For structures which are composed of a variety of material types, the application and interpretation of enhanced load qualification tests must address the effects of enhanced loading on each type of material in the fully assembled structure in the context of the total SIA program. The convenience of using load enhancement in evaluation of the design using one type of material must be assessed in relation to the potential penalty of overdesigning components made from a different type of material. The magnitude of the factor of safety for qualification testing of the maximum loading resistance SI parameter and methods of qualification testing for maximum loading resistance SI parameter for structure, which is composed of different types of materials, shall be as specified by the Army Generic SIA Program Specification Process, Appendix A.

Proper simulation of certain loading conditions may require preloading to account for the influence of prior loading upon material behavior related to the test condition. For example, to properly evaluate the tensile loading conditions which may occur in some portion of a projectile when exiting a gun barrel, it may be necessary to preload the structure in compression to include the effects of "set back" launch loads on material behavior in the region of interest. Similarly, the proper evaluation of SI for loading conditions for ballistic missile reentry loads may require prior application of launch loads. The effect of such loading sequences on material property or allowables such as yielding or ultimate strength failure or flaw based fracture was discussed in Task II-D.

At the completion of loading to the levels required for qualification testing and completion of the evaluation of those tests, it may be useful to load the structure to produce a major structural failure in order to assess the potential for increased SI capability of the structure and to improve the understanding of failure mode behavior in the fully assembled structure.

Task IV-A4. Instrumentation

Qualification tests shall be carefully instrumented to quantify levels of measures explicitly involved in modeling this SI parameter (see Task II-F), or as supplemental criteria (see Task I-B6) such as flaw or damage initiation and growth, deflection, and local yielding or buckling. In addition, it may be necessary to quantify correlating parameters associated with environmental effects measured in material allowable or design development tests. It is particularly important for proper test evaluation that instrumentation be able to provide data which can be used to assess when particular events related to SIA occur during qualification testing. Specialized instrumentation may be required for some tests. For welded structures or advanced materials, the use of acoustic emission indications, which correlate with plastic flow or small scale damage initiation and growth, may be useful in assessing whether behavior is within specified limits (see Task I-B6).

The instrumentation planning shall be guided by associated analyses, but shall also consider provisions for monitoring events which may not be predicted by the analyses.

Task IV-A5. Posttesting Inspection

After completion of the maximum loading resistance qualification testing, the structural components shall be thoroughly inspected for cracking, damage, excessive local or global deformation, local plastic flow, or buckling. The structure shall be disassembled to the extent necessary to perform inspections. Inspections shall focus on critical issues and regions explicitly involved in SIA predictions and measurement criteria (see Task I-B6). In particular, careful attention should be given to inspection of joints where effects of joining methods and local stress or strain gradients are likely to adversely effect SI. Redundant load paths shall be carefully inspected since damage in one of the paths may not be easily detected. Inspection methods shall be consistent with predictive models in terms of sensitivity, resolution, and field of measurement.

In addition, the structure shall be inspected for damage in regions which were not expected to be sites of important damage on the basis of the predictive models.

Task IV-A6. Test Evaluation

The evaluation of the maximum loading resistance SI parameter shall be based on the ability of the structure to resist the qualification test loading, and on an assessment of the "condition of the structure" at the completion of the test as specified in Task I-B6, the manufacturing quality control program (see Task II-F1), and the in-service maintenance and quality program (see Task IV-F4 and Task IV-F5). The test failure modes shall be evaluated to verify that they are consistent with the analytical predictions (see Task III-F). The evaluation shall be used to support rationale for modifications of analyses, as needed, which shall become part of the final analyses summary (see Task IV-F2). Criteria for acceptable performance in terms of the maximum loading resistance SI parameter shall be specified by the mission specific SIA standard and specifications.

Task IV-B. Service Life - Base Line Design Qualification Testing

Task IV-B1. Structure

The Army generic SIA program requires that qualification testing of the service life - base line design SI parameter shall test fully assembled structures with the updated design configuration of the materiel system to the extent that it is practical. The fully assembled structure shall be in accordance with the details specified by the Army Generic SIA Program Specification Process, Appendix A. Testing in such a configuration is intended to permit qualification testing of the entire structure where critical parts are assembled in actual design conditions. In addition, structural damage or failure of parts or regions of parts which may not have been predicted by the service life analysis or design development testing can be detected and evaluated.

If the analysis modeling method is flaw or damage based, the test structure shall contain the base line design initial quality flaw or damage size, as specified in service life analyses - base line design (see Task II-G2), in the most critical locations.

Task IV-B2. Number of Tests

The number of qualification tests required to evaluate the service life - base line design SI parameter depends upon material variability, the modeling method, the design concept (structurally redundant, damage containment, and damage detection/leak before break), whether test results are in terms of life related to a specific loading spectrum or strength associated with a specific life, factor of safety for service life - base line design qualification testing, service life scatter factor for base line design qualification testing (see Task I-B7), test data from design development testing (see Task III), historical data base from similar materiel system designs and in-service usage, and the consequences of failure. For some materiel system designs using advanced materials where material properties are best characterized on a statistical basis (see Task II-D), the number of tests may be most meaningful if it is determined on a statistical basis. The number of tests required shall be specified by the Army Generic SIA Program Specification Process, Appendix A.

Task IV-B3. Load and Environment

Test loading shall simulate actual loading distributions including complex loadings and loading rate. The test loading distributions shall be based upon the service load analyses (see Task II-A and Task II-B).

Qualification tests shall account for environmental effects either by direct environmental testing, by preconditioning, load enhancement related to material property environmental "knockdown factors," or by correlation with design development environmental data on the basis of a correlating mechanics parameter. The environment shall be consistent with the results of the design environmental analysis (see Task II-C) and the environmental design development testing (see Task III-A). If a load enhancement approach is used, damage or failure modes in the qualification tests must be the same as in the service life analyses (see Task II-G2) and material property, or allowable tests (see Task II-D) on which the load enhancement is based.

In general, qualification service life tests should account for dynamic loading effects. Dynamic loading issues are similar to those discussed in Task IV-A.

The qualification test load spectrum and deterministic load sequence or interaction effects shall be consistent with the results of the service load analyses (see Task II-B) and service load design development testing (see Task III-A and Task III-E). The Army generic SIA program requires, in general, that the qualification test spectrum shall include all significant effects of load level and load sequence or interaction relevant to the design concept, local design details, configuration, size, and material. Qualification test methods which rely upon damage accumulation hypotheses or empirical test data shall be supported by careful documentation of bases and supporting data, as referred to in Task II-G and Task III-E, in order to clearly indicate the design conditions for which these methods are applicable.

The loading magnitude shall be derived from the service load analyses (see Task II-B), the service load design development testing (see Task III-A), the factor of safety for service life base line qualification testing (see Task I-B7a), and load enhancements. The load enhancements account for the environmental and dynamic effects stated previously (see Task IV-A3) and for testing of some advanced materials. This load enhancement may be applied to qualification testing of advanced materials for which service life tests exhibit a

relatively large amount of scatter and a relatively flat stress/strain versus life behavior. A shorter, more practical qualification test duration may be possible based upon a load enhancement and a smaller service life factor. For structures which contain a variety of classes of materials, qualification testing with enhanced loads and the interpretation of results must be considered in the context of the total SIA program for the materiel system, as discussed in Task III-A. The methods of simulation for environment and dynamic effects, load spectrum, and deterministic load interaction effects shall be as specified by the Army Generic SIA Program Specification Process, Appendix A.

For materiel systems where the influence of long-term environmental degradation upon load resistance of the materiel system may be the dominant service life issue, qualification testing may be practical only with enhanced loads or with an environment of increased severity. Qualification testing based on such simulations shall be in accordance with methods specified by the Army Generic SIA Program Specification Process, Appendix A.

Task IV-B4. Test Duration

Qualification test duration shall be sufficient to permit evaluation of the service life base line SI parameter relative to the total number of each of the critical structural components for the specified design life of the components. This evaluation may involve SI related to inspection interval or to total life.

For components which are required to demonstrate a fatigue strength or strain level at a specified design life basis, the test duration shall be equal to the design life. The specified life may represent an approximation of an infinite life, or may represent a design based on apparent endurance limit fatigue strength. For such designs, the uncertainties related to analysis, testing, and material property variability are accounted for by a specified factor of safety for service life - base line design for qualification testing (see Task I-B7a) or by statistical interpretation of repeated tests.

For components which are required to demonstrate a specified service life or a period of SIA related to an inspection interval for a specified loading spectrum, the test duration shall be equal to the product of the service life or inspection interval and the specified scatter factor for service life - base line design.

For materiel systems where a very large number of fatigue cycles would be required for qualification testing at nominal load levels, a hybrid service life scatter factor may be applied associated with enhanced load levels as stated in the discussion of load and environment in this task and in Task I-B7b.

The basis for qualification testing, life or strength, and the related factor of safety or statistical strength basis and hybrid service life scatter factor approach shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A.

Task IV-B5. Residual Strength

Upon completion of the service life test duration period, a residual strength/resistance to maximum loading test shall be applied when required for the materiel system as summarized in the service life SIA plan (see Task I-D). A residual strength is required typically for flaw based parameter models and may, in principle, be required for nonflaw based parameter

models. The test load level shall account for the basic materiel system residual strength requirement and all uncertainties and variabilities. The test level may be related to the basic residual strength requirement on a statistical basis where appropriate. The residual strength qualification tests shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A.

Task IV-B6. Instrumentation and Posttest Inspection

The service life instrumentation shall possess the attributes and assess the issues as discussed with respect to the maximum loading parameter (see Task IV-A). For service life qualification testing, the instrumentation shall assist in the interpretation of events such as flaw or damage initiation and growth, including behavior of redundant load paths and verification of design concepts such as damage containment, crack arrest, leak before break, and damage monitoring. The posttest inspection shall be conducted as specified in Task IV-A5.

Task IV-B7. Test Evaluation

The evaluation of the service life base line design SI parameter shall be based on the capability of the structure to resist the prescribed loading for the qualification test duration, and to resist the residual strength test loading while meeting the condition of structure requirements (see Task I-B6). In addition, the evaluation shall consider an assessment of the behavior of the structure in relation to the performance of the design concepts such as redundant load paths, damage arrest and containment, and damage detection, including "leak before break." The assessment of a redundant load path structure shall include the capability of the structure which remains after failure of one of the paths to resist continuing damage until failure of the first path has been detected and life maintenance provisions implemented.

Qualification test failure modes shall be evaluated to verify that they are consistent with service life analyses (see Task II-G2) and design development testing (see Task III-E). The analyses shall be modified as needed and documented in the final SI analysis summary (see Task IV-F2). The evaluation of the service life base line design SI parameter shall be in accordance with the mission specific SIA standards and specifications.

Task IV-C. Service Life - Design Sufferance Qualification Testing

Task IV-C1. Structure

The Army generic SIA program requires qualification testing to evaluate the service life design sufferance SI parameter. The qualification testing shall be consistent with the issues selected and the design basis developed in the service life plan (see Task I-D), service life design sufferance analyses (see Task II-G3), and service life design sufferance design development testing (see Task III-F).

The test structure shall be a fully assembled structure with the updated design configuration to the extent that is practical. The details of the fully assembled structure shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A.

The initial quality of the structure, in terms of flaw or damage sites and surface conditions, all relating to the most critical locations, shall be consistent with analysis and modeling

methods discussed in Task II-G3, and development test results (see Task III-F), and shall be in accordance with the mission specific SIA standard and specifications.

Task IV-C2. Number of Tests

The number of qualification tests required to evaluate the service life - design sufferance SI parameter depends upon material variability, the modeling method, the design concept (structural redundancy, damage containment, damage detection/leak before break), whether test results are in terms of life at a specific loading spectrum or strength associated with a specific life, factor of safety for service life design sufferance qualification testing, service life scatter factor for design sufferance qualification testing (see Task I-B7), test data from design development testing (see Task III), historical data bases from similar materiel system designs and in-service usage, and the consequences of failure. For some materiel system designs using advanced materials where material properties are best characterized on a statistical basis (see Task II-D), the number of tests may be most meaningful if determined on a statistical basis. The number of tests required shall be specified by the Army Generic SIA Program Specification Process, Appendix A.

Task IV-C3. Load and Environment

Test loading shall simulate actual loading distributions, including complex loadings and loading rate. The test loading distributions shall be based upon the service load analyses (see Task II-A and Task II-B).

Qualification tests shall account for environmental effects either by direct environmental testing, by preconditioning load enhancement related to material property environmental "knockdown factors," or by correlation with design development environmental data on the basis of a correlating mechanics parameter. The environment shall be consistent with the results of the design environmental analysis (see Task II-C), and the environmental design development testing (see Task III-A). If a load enhancement approach is used, damage or failure modes in the qualification tests must be the same as in the service life analyses (see Task II-G3) and material property or allowable tests (see Task II-D) on which the load enhancement is based.

In general, qualification service life tests should account for dynamic loading effects. Dynamic loading issues are similar to those discussed in Task IV-A.

The qualification test load spectrum and deterministic load sequence or interaction effects shall be consistent with the results of the service load analyses (see Task II-B) and service load design development testing (see Task III-A and Task III-E). The Army generic SIA program requires, in general, that the qualification test spectrum shall include all significant effects of load level and load sequence or interaction relevant to the design concept, local design details, configuration, size, and material. Qualification test methods which rely upon damage accumulation hypotheses or empirical test data shall be supported by careful documentation of bases and supporting data referred to in Task II-G and Task III-E, in order to clearly indicate the design conditions for which these methods are applicable.

The loading magnitude shall be derived from the service load analyses (see Task II-B), the service load design development testing (see Task III-A), the factor of safety for service life design sufferance qualification testing (see Task I-B7a), and load enhancements. The load

enhancements account for the environmental and dynamic effects stated previously (see Task IV-A) and for testing of some advanced materials. This load enhancement may be applied related to qualification testing of advanced materials for which service life tests exhibit a relatively large amount of scatter and a relatively flat stress/strain versus life behavior. A shorter, more practical qualification test duration may be possible based upon a load enhancement and a smaller service life factor. For structures which contain a variety of classes of materials, qualification testing with enhanced loads and the interpretation of results must be considered in the context of the total SIA program for the materiel system as discussed in Task III-A. The methods of simulation for environment and dynamic effects, load spectrum, and deterministic load interaction effects shall be as specified by the Army Generic SIA Program Specification Process, Appendix A.

For materiel systems where the influence of long-term environmental degradation upon load resistance of the materiel system may be dominant, service life issue qualification testing may be practical only with enhanced loads or with an environment of increased severity. Qualification testing based on such simulations shall be in accordance with methods specified by the Army Generic SIA Program Specification Process, Appendix A.

Task IV-C4. Test Duration

Qualification test duration shall be sufficient to permit evaluation of the service life design sufferance SI parameter relative to the total number of each of the critical structural components for the specified design life of the components. This evaluation may involve SI related to inspection interval or to total life.

For components which are required to demonstrate a fatigue strength or strain level at a specified design life basis, the test duration shall be equal to the design life. The specified life may represent an approximation of an infinite life or may represent a design based on apparent endurance limit fatigue strength. For such designs, the uncertainties related to analysis, testing, and material property variability are accounted for by a specified factor of safety for service life design sufferance for qualification testing (see Task I-B7a) or by statistical interpretation of repeated tests.

For components which are required to demonstrate a specified service life or a period of SIA related to an inspection interval for a specified loading spectrum, the test duration shall be equal to the product of the service life or inspection interval and the specified scatter factor for service life design sufferance.

For materiel systems where a very large number of fatigue cycles would be required for qualification testing at nominal load levels, a hybrid service life scatter factor may be applied associated with enhanced load levels as stated in the discussion of load and environment in this task and in Task I-B7b.

The basis for qualification testing, life or strength, and the related factor of safety or statistical strength basis and hybrid service life scatter factor approach shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A.

Task IV-C5. Residual Strength

Upon completion of the service life test duration period, a residual strength/resistance to maximum loading test shall be applied, when required, for the materiel system as summarized in the service life SIA plan (see Task I-D). A residual strength is required, typically, for flaw based parameter models and may, in principle, be required for nonflaw based parameter models. The test load level shall account for the basic materiel system residual strength requirement and all uncertainties and variabilities. The test level may be related to the basic residual strength requirement on a statistical basis, where appropriate. The residual strength qualification tests shall be in accordance with the Army Generic SIA Program Specification Process, Appendix A.

Task IV-C6. Instrumentation and Posttest Inspection

The service life instrumentation shall possess the attributes and assess the issues as discussed with respect to the maximum loading parameter (see Task IV-A). For service life qualification testing, the instrumentation shall assist in the interpretation of events such as flaw or damage initiation and growth, including behavior of redundant load paths and verification of design concepts such as damage containment, crack arrest, leak before break, and damage monitoring. The posttest inspection shall be conducted as specified in Task IV-A5.

Task IV-C7. Test Evaluation

The evaluation of the service life design sufferance SI parameter shall be based on the capability of the structure to resist the prescribed loading for the qualification test duration and to resist the residual strength test loading while meeting the condition of structure requirements (see Task I-B6). In addition, the evaluation shall consider an assessment of the behavior of the structure in relation to the performance of the design concepts such as redundant load paths, damage arrest and containment, and damage detection, including "leak before break." The assessment of a redundant load path structure shall include the capability of the structure which remains after failure of one of the paths to resist continuing damage until failure of the first path has been detected and life SIA maintenance provisions are implemented.

Qualification test failure modes shall be evaluated to verify that they are consistent with service life analyses (see Task II-G3) and design development testing (see Task III-E). The analyses shall be modified, as needed, and documented in the final SI analysis summary (see Task IV-F2). The evaluation of the service life base line design SI parameter shall be in accordance with the mission specific SIA standards and specifications.

Task IV-D. Limited Duration Service Life Qualification Testing

Task IV-D1. Unrepaired Damage Qualification Testing

The Army generic SIA program requires qualification testing to evaluate the limited duration service life - unrepaired damage SI parameter which characterizes the SIA aspect of survivability. The test structure shall be a full-sized structure incorporating updated design details containing the damage specified by the Army Generic SIA Specification Process, Appendix A, which may be included in the service life SI plan (see Task I-D). The location of the damage and the extent of surrounding nominal structure necessary for a representative test

shall be as determined by the limited duration service life analyses (see Task II-H2) and development tests (see Task III-G1).

The number of tests, load levels and spectra, and test environment are, in general, dependent upon all of the issues stated with respect to base line design (see Task IV-B). The values of factor of safety for service load, residual strength, and the service life factor are as specified for qualification testing of limited duration service life unrepaired damage (see Task I-B7). In addition, the qualification test shall account for the effects of service environment prior to the damage event and the potential for increased environmental effects during the period of unrepaired damage.

Test instrumentation shall provide data to permit interpretation of results as discussed in Task IV-B. In particular, test instrumentation shall provide for an evaluation of the damage resistant design concepts such as redundant load paths and damage arrest or containment designs.

The evaluation of the qualification test of the limited duration service life SI parameter shall consider the results of the test duration and residual strength test, if required, and supplemental requirements for "condition of structure" related to this SI parameter (see Task I-B6). Particular attention should be given to the SI of the nominal structure surrounding the damage for condition of the structure produced by local stress distributions and environmental effects which differ from those related to base line and design sufferance.

Task IV-D2. Repaired Damage Qualification Testing

The Army generic SIA program requires qualification testing to evaluate the limited duration service life repaired damage SI parameter. The test structure shall be a full-sized structure incorporating updated design details containing repaired damage specified by the Army generic SIA program specification and which may be included in the service life SIA plan (see Task I-D). The location of the repaired damage and the extent of surrounding nominal structure necessary for a representative test shall be as determined by the limited duration service life analyses (see Task II-H2) and design development tests (see Task III-G2).

The number of tests, load levels and spectra, and test environment are, in general, dependent upon all of the issues stated with respect to the base line design (see Task IV-B) where values of safety for service load and residual strength and the service life factor are as specified for qualification testing of limited duration service life repaired damage (see Task I-B7). In addition, the qualification test shall account for the effects of service environment prior to the damage event, after the damage event prior to repair, and the environmental effects during the period of repaired damage.

Test instrumentation shall provide data to permit interpretation of results as discussed in Task IV-B. In particular, test instrumentation shall provide for an evaluation of design concepts such as behavior of redundant load paths.

The evaluation of the qualification test of the limited duration service life SI parameter shall consider the results of the test duration and residual strength test, if required, and the supplemental requirements for "condition of structure" related to this SI parameter (see Task I-B6). Particular attention should be given to the SI of the nominal structure

surrounding the repair for "condition of structure" produced by the local stress distributions and environmental effects which differ from those related to base line and design sufferance.

Task IV-E. Qualification Test Summary and Corrective Actions

The Army generic SIA program requires that the materiel system developer shall analyze all SIA problems revealed by qualification testing such as failure by yielding, cracking, fracture, excessive deformation, buckling or loss of rigidity or deficiencies in behavior of design features such as redundant load path structure, crack arrest, damage containment, and damage detection, including a leak-before-break basis. The materiel system developer shall devise solutions to problems and assess the ramifications upon overall materiel system development in terms of cost, schedule, and readiness. If design modifications to correct deficiencies are to be implemented, they shall be evaluated by application of the detailed SIA requirements of the Army generic SIA program.

Task IV-F. Life Management Data Package

In order to maintain the SI of a fielded system, it is necessary that the SIA management function (see Task V-A) be capable of performing specific structural maintenance and inspection programs, in-service monitoring, critical part replacement, and materiel system structural modifications which are consistent with all aspects of the overall SIA program. In order to properly perform these tasks, a detailed life management data package is required which documents the manufacturing quality control final summary, the SI final analyses summary, the material system operational limitation plan, the life SIA maintenance plan, the in-service monitoring plan, and the data bank and reporting plan.

Task IV-F1. Manufacturing Methods and Quality Control Final Summary

The Army generic SIA program requires that a manufacturing methods quality control final summary be prepared by the materiel system developer. The final summary shall contain all the information in the initial summary (see Task III-H), modified to reflect manufacturing methods and quality control changes and additions occurring during qualification testing. In addition, the summary shall establish methods to certify and monitor subcontractors, vendors, and suppliers. If critical parts are manufactured by new vendors after qualification testing of structures manufactured by initial vendors, the Army generic SIA program requires qualification testing of critical parts manufactured by new vendors. The final manufacturing methods and quality control final summary shall be maintained by the SIA management function (see Task V-A) to reflect changes after the materiel system is in service.

Task IV-F2. SI Final Analysis Summary

The Army generic SIA program requires the documentation of the analyses for each of the SI parameters which characterize the SI of the materiel system. The SI analysis final summary shall document the results of design analyses (see Task II) and any modifications which are necessary as a result of design development testing (see Task III) and qualification testing (see Task IV). The analyses summary shall document the rationale and supporting bases for modeling methods, failure criteria, value of factor of safety and service life factors, statistical bases for material properties, service life - base line initial quality, service life - design sufferance issues resolution, service life - limited duration design issues evaluated, residual strength requirements, damage accumulation and degradation models, "end of service life"

definition, methods for quantifying environmental effects, size effect, dynamic loading effects, accelerated testing, and the building block testing approach (see Task III-C). The SI analyses shall identify critical areas of critical parts, associated critical flaw or damage sizes, inspection intervals and retirement lives, where appropriate.

The analyses methods shall be expressed on fundamental bases, minimizing empirical bases to the extent feasible, to clarify the rationale supporting the methods and to permit new data from in-service monitoring and life maintenance inspections (see Task V) to be most readily assessed.

Task IV-F3. Materiel System Operational Limitation Plan

The Army generic SIA program requires the materiel system developer to identify the nominal materiel system operational limitations based on the particular materiel system mission as stated in the SIA plan (see Task I-A), the design service life and usage (see Task I-E), the documented SI characterization of the system (see Task IV-F2), and the requirements of the mission specific SIA standards and specifications. The nominal operations shall be expressed in terms of percentage of service life associated with specific system configuration and use, where appropriate. The absolute magnitude of loading resulting from any one event may be limited by the specified control of materiel system usage.

The plan shall prescribe positive measures to prevent exceeding the nominal operational limitations, or if such limitations are not feasible or desireable, procedures for recording and documenting their occurrence shall be part of the life maintenance program. The operational limitations for limited duration service life shall be identified, where appropriate, consistent with design service life and usage (see Task I-E), the SI characterization of the system, and the mission specific SIA standards and specifications. Operational limitations shall be prescribed for both unrepaired damage and repaired damage where appropriate.

Task IV-F4. Life SIA Maintenance Plan

The Army generic SIA program requires that the materiel system developer shall prepare a plan which describes the inspection, maintenance, replacement of parts, and modifications to assure SIA of the materiel system. The life SIA maintenance plan shall be consistent with constraints of an achievable program specified by the mission specific SIA standard and specification in terms of the type of inspection and maintenance facility, the frequency of inspection, and the amount of disassembly of structure required. The plan shall be consistent with the SI design, analysis, modeling, material properties, and associated issues related to service life as characterized by the service life base line design and design sufferance and limited duration SI parameters. The plan shall also contain provisions for general structural inspection and maintenance for unanticipated structural damage and deficiencies not specifically identified in the SIA program.

The structural maintenance plan shall identify expected critical locations of structural parts, the inspection factor (specified flaw, damage, or surface condition) and the criteria for assessing the results. If SI parameters are expressed explicitly in terms of flaw or damage criteria, the plan shall provide for inspection of flaw or damage sizes based on these criteria.

The plan shall also include inspection methods to assure SI based on the service life design sufferance SI parameter. The design sufferance based inspections may involve either

explicit flaw or damage criteria or inspection factors which are necessary to assure SI such as beneficial residual stresses and surface treatment or coating which inhibit flaw or damage initiation or environmental damage. The inspection for flaw or damage based design sufferance SI parameters should be based explicitly on specifications derived from the SI analyses final summary (see Task IV-F2).

For materiel systems relying upon flaw or damage detectors, inspection and maintenance criteria shall be developed to ensure that the detectors are operating properly in service. For systems with redundant load paths or crack arrest or containment design, inspection criteria should be developed based on the SI analyses final summary to ensure that these design features have not been degraded in service.

If proof tests are considered for in-service quality control, the associated structural effects throughout the entire structure shall be evaluated; in particular, the potential detrimental effects of inelastic deformations or damage initiation upon SIA.

The SIA maintenance plan may consider, if feasible, a lead force program. The lead force units would be scheduled to experience the more severe type of service described in the mission or service life usage (see Task I-A and Task I-E) early in their service life along with more frequent and extensive inspection in order to obtain an early indication of SI deficiencies. The SIA maintenance plan shall specify detailed repair procedure for critical parts based on the SI analyses (see Task IV-F2) which do not compromise SI during either repair or subsequent service.

The plan shall include, when necessary, inspection and maintenance actions related to the degradation in resistance to maximum loading SI parameters.

The plan shall include provisions to assist in the recognition of potentially serious SIA deficiencies which shall be reported to the in-service SI data bank and reporting function (see Task V-E) for subsequent feedback to the SIA management function task (see Task V-A). The plan may include SIA training (recognition of important in-service SIA issues) for the materiel system operational and maintenance personnel.

Task IV-F5. In-Service Usage Monitoring Plan

The Army generic SIA program requires that an in-service usage monitoring plan be established by the materiel system developer which is directly related to important SI measures as documented in the SI final analysis summary (see Task IV-F2). In-service materiel system usage, loading, and environment may differ substantially from the anticipated design loading and environmental spectra associated with the SI final analyses summary. Excluded from this requirement are materiel systems where in-service usage variations are not an issue such as single usage systems, typically, missile and projectile systems. For complex materiel systems, important quantities to be monitored in service would be time histories of stress/strain, velocities, acceleration, temperature, and environment at locations selected on the basis of the SI final analyses summary. All force units which are not fully instrumented shall be monitored on a simple basis such as center of gravity motions for airborne systems and automatic or manual counting of primary usage cycles related to SIA of other materiel systems. The plan shall establish individual identification of critical components. A lead force program, as described in Task IV-F3, may be useful for in-service usage monitoring in order to achieve early indications of actual loading during service usage. The plan shall make provisions to

detect changes in usage relative to the mission usage in qualification tests (see Task IV) and to report these findings and all in-service data to an in-service data bank (see Task V-E). The plan shall identify the nature and scope of the in-service monitoring program including the number of units associated with each type of monitoring. The in-service monitoring plan shall be an achievable program consistent with the type of monitoring system and the frequency and nature of information transfer in accordance with the mission specific SIA standard.

Task IV-F6. SIA Data Bank and Reporting Plan

The materiel system developer shall establish a plan to collect SIA data from the life maintenance program (see Task V-C) and the in-service monitoring program (see Task V-D). The data shall include SI deficiencies and in-service usage deviations reported by these programs. The data shall be retained in the data bank in readily accessible form, and pertinent data shall be reported to the SIA management function (see Task V-A).

Task IV-G. SIA Evaluation

The Army generic SIA program requires that the SIA of each critical component of the materiel system shall be evaluated on the basis of a total SIA characterization based on the following.

- Qualification test results (Task IV-E)
- Manufacturing QA summary (Task IV-F1)
- Validated SI analysis (Task IV-F2)
- In-service maintenance and monitoring program (Task IV-F4 and Task IV-F5)

The acceptance criteria and interpretation of the qualification test results, the life maintenance plan, and in-service monitoring plan shall be in accordance with the mission specific SIA standards and specifications.

Task V. Life Management

In order to maintain the SI of a fielded system, it is necessary to perform specific structural maintenance, inspection, in-service monitoring, and life management functions consistent with the overall materiel system SIA program.

Task V-A. SIA Management

The Army generic SIA program requires that an SIA management function be established for each materiel system. The management activities shall be based on an integrated SIA perspective as documented by the life management data package (see Task IV-F). The activities shall be based on thorough understanding of the materiel system design analysis, development and qualification programs, and documentation. The management function shall also initiate actions related to in-service SI deficiencies, unanticipated loadings reported from the data bank (see Task V-E), mission modifications, or life extension programs. Significant structural modifications made after qualification testing must be assessed on the basis of the SI parameters defined by this program by qualification testing and evaluation.

Task V-B. Materiel System Operational Limitation Program

The SIA management function shall implement the materiel system operational limitation plan (see Task IV-F3) in accordance with the mission specific SIA standards and specifications.

Task V-C. Life SIA Maintenance Program

The SIA management function shall implement the life structural maintenance plan (see Task IV-F4) in accordance with the mission specific SIA standards and specifications.

Task V-D. In-Service Usage Monitoring Program

The SIA management function shall implement the in-service usage monitoring plan (see Task IV-F5) in accordance with the mission specific SIA standards and specifications.

Task V-E. SIA Data Bank and Reporting Program

The SIA management function shall implement the SIA data bank and reporting plan (see Task IV-F6) in accordance with the mission specific SIA standards and specifications.

APPENDIX A. ARMY GENERIC SIA PROGRAM SPECIFICATION PROCESS

1. The Army generic SIA program states a particular SIA factor, e.g., FOS, service life factor, modeling methods, etc., which must be specified in the SIA program.

2. The Army generic SIA program states relevant issues which are to be considered in specifying the particular SIA factor.

3. The mission specific SIA standards and specifications shall specify the particular SIA factor for specific classes of structure consistent with the Army Generic SIA Technology Program issue guidelines to the extent feasible. Supporting rationale and bases consistent with the generic program issue guidelines shall be documented in the mission specific standards and specifications.

4. If the mission specific SIA standards and specifications have not specified a particular SIA factor stated in the Army generic SIA program, the materiel system developer shall determine the SIA factor consistent with the issues and guidelines stated in the Army generic SIA program. The materiel system developer shall document the rationale and supporting data consistent with the generic program issue guidelines when required by the Army generic program. The appropriate Army command shall approve the action taken by the materiel system developer.

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William T. Matthews

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Key Words

Structural engineering
Structural mechanics
Mechanical properties

A Generic Structural Integrity Assurance Technology Program is presented which is applicable to all Army materiel systems. The technology program is organized and written in the format of a standard to demonstrate the potential for formalized program development. The relationship between such a program and possible Army and U.S. Army Materiel Command (AMC) regulations is indicated. The program covers all tasks over the life of the system, design information, analysis and material characterization, design development testing, qualification testing, and life management. The generic program requires the development of mission specific structural integrity programs for particular classes of materiel structures based on the generic program guidelines. The generic program incorporates a new generalized concept which defines structural integrity parameters for resistance to maximum loading and service life. These parameters must be evaluated on the basis of an integrated qualification testing and in-service program by acceptance criteria formally specified by the major subordinate command. A service life base line parameter is defined which characterizes the nominal behavior of a system. A service life design sufferance parameter is defined and illustrated which characterizes "other than nominal" conditions which are a major influence on safety. Design sufferance conditions are general and may involve damage tolerance or any other design conditions which may deviate from base line conditions. Limited duration service life unrepaired/repaired damage parameters are defined for those unique design conditions. The generalized approach requires that detailed structural quantities must be defined and supporting basis and rationale documented.

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